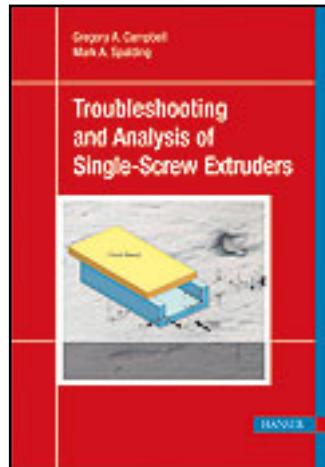


# HANSER



## Preface

Gregory A. Campbell, Mark A. Spalding

Analyzing and Troubleshooting Single-Screw Extruders

ISBN (Buch): 978-3-446-41371-9

ISBN (E-Book): 978-3-446-43266-6

For further information and order see

<http://www.hanser-fachbuch.de/978-3-446-41371-9>

or contact your bookseller.

# Preface

Classically, all prior extrusion books are based on barrel rotation physics. Literature developed over the past 15 years has led to this first book to be published based on the actual physics of the process—screw rotation physics. After the theories and the math models are developed in the first nine chapters, the models are then used to solve actual commercial problems in the remainder of the book. Realistic case studies are unique in that they describe the problem as viewed by the plant engineers and provide the actual dimensions of the screws. Knowledge is developed using a series of hypotheses that are developed and then tested, which allows a series of technical solutions. Several actual solutions are proposed with the final results that solve the problem then clearly presented. Overall, there is not a book on the market with this level of detail and disclosure. New knowledge in this book will be highly useful for production engineers, technical service engineers working with customers, consultants specializing in troubleshooting and process design, and process researchers and designers that are responsible for processes that run at maximum rates and maximum profitability.

Debugging and troubleshooting single-screw extruders is an important skill set for plant engineers since all machines will eventually have a deterioration in their performance or a catastrophic failure. Original design performance must be restored as quickly as possible to mitigate production losses. With troubleshooting knowledge and a fundamental understanding of the process, the performance of the extruder can be restored in a relatively short time, minimizing the economic loss to the plant. Common root causes and their detection are provided. Hypothesis testing is outlined in Chapter 10 and is used throughout the troubleshooting chapters to identify the root causes. Elimination of the root cause is provided by offering the equipment owner several technical solutions, allowing the owner to choose the level of risk associated with the process modification. Mechanical failures are also common with single-screw extruders, and the common problems are identified. Illustrations are provided with the problems along with many numerical simulations of the case studies. Collectively, these instruct the reader on how to determine and solve many common extrusion problems. About 100 case studies and defects are identified in the book with acceptable technical solutions. Lastly, we

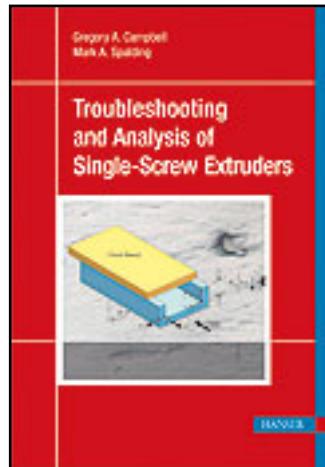
hope that this book provides the information and technology that is required for the understanding, operation, and troubleshooting of single-screw extruders.

*Gregory A. Campbell*

*Mark A. Spalding*

The views and opinions expressed in this book are solely those of the authors and contributors. These views and opinions do not necessarily reflect the views and opinions of any affiliated individuals, companies, or trade associations.

# HANSER



Sample Pages

Gregory A. Campbell, Mark A. Spalding

Analyzing and Troubleshooting Single-Screw Extruders

ISBN (Buch): 978-3-446-41371-9

ISBN (E-Book): 978-3-446-43266-6

For further information and order see

<http://www.hanser-fachbuch.de/978-3-446-41371-9>

or contact your bookseller.

# 12

## Flow Surging

Flow surging is defined as the oscillatory change in the rate of the extruder while maintaining constant set point conditions. Flow surging can originate from many different sources including improper solids conveying, melting instabilities, flow restrictions, and improper control algorithms [1–5]. Surging in most cases results in lower production rates, higher scrap rates, higher resin consumption, material degradation, and higher labor costs. In mild cases, flow surging will cause plant personnel to set the product at the low end of the dimension setting at the low rate portion of the surge. At the high rate portion of the surge, the dimensions of the product will be oversized. Oversized products will use more resin than necessary, adding cost to the product and decreasing the profitability of the plant. Obviously, a process that is very steady has the capability of minimizing resin usage and thus maximizing the profitability of the process. For a profile process where the dimension of the cross section is critical to downstream assembly processes, the extreme ends of the rate surges may result in a product that is outside of the specification, and some profiles will need to be scrapped or recycled. In this chapter numerous case studies along with diagnostic methods are presented for processes that flow surge.

The additional cost of producing products from a line that is flow surging can be substantial. If the flow surge is not too large and the line can be operated, the instability of mass flow at the die can cost the converter from 5 to 15% added costs in resins. The higher resin costs are incurred because the dimensions of the articles are larger or thicker than needed. For example, if a line is producing sheet for a downstream thermoforming process and it is operating unstably, then some thermoformed parts will have an acceptable mass while others will have a higher mass, costing the plant more in resin. Often the instability occurs only at a high rate while at lower rates the process is stable. In this case the plant may miss shipment dates since the line can only be operated at a fraction of its capacity, or the plant may incur higher labor costs because the line will need to operate over weekends. In severe cases, flow surging can cause the line to be incapable of producing product at any rate. Thus, in order to produce product at the lowest possible cost, the line must be operating stably so that the rate and product quality are maximized.

Processes that flow surge will often cause a higher level of degradation products to occur in the extrudate. For these cases, the unsteady nature of the flows in the screw channels will tend to break off small levels of degradation products adhering to the screw. The degradation products could occur at the flight radii and regions with long residence times, and they may not contaminate the extrudate under normal conditions. But the unsteady-state nature of the flow surge will tend to break them away from the screw surface.

## ■ 12.1 An Overview of the Common Causes for Flow Surging

Improper process temperatures and poor temperature controls are common root causes for flow surging. For example, solids conveying depends on a balance of the forwarding forces at the barrel wall and the pushing flight and the retarding forces at the screw surface. These forces depend mainly on the geometry of the channel and are directly proportional to the coefficient of dynamic friction for temperatures less than the melting (or devitrification) temperature and on viscous forces for higher temperatures [6]. Since the coefficient depends on temperature, pressure, and velocity [7], surface temperature changes for the barrel and screw in the feeding section will strongly affect the performance of the extruder. If the surface temperatures become too different from the optimal values, flow surging and loss of specific rate will occur. If the solids-conveying section of the extruder is controlling rate, not the metering section as designed, then a portion of the screw channel between the sections will be partially filled at the low-rate swing of the cycle and most often will be completely filled at the high-rate region of the cycle.

Improper design and operation of the melting section of the screw can lead to extrusion instabilities. For example, solid bed breakup [3] can cause solids to migrate downstream. These solids can wedge into other sections of the screw and cause the extruder to flow surge [2, 4] or cause the extrudate to have periodic changes in temperature. Periodic changes in discharge temperature will cause some level of flow surging at the die [8].

### 12.1.1 Relationship Between Discharge Pressure and Rate at the Die

Dies are shaping devices that operate at a rate that is directly proportional to the upstream pressure. Thus, if the pressure to the die is not constant then a variable rate will occur at the die opening, causing the dimensions of the product to vary. Rate surges at the die can be estimated from the pressure surges using the

following equations for flow through a cylindrical restriction (or die) for a power law fluid [4]:

$$\Delta Q = (Q_1 - Q_2) / Q_1 = 1 - (1 - \Delta P)^{1/n} \quad (12.1)$$

$$\Delta P = (P_1 - P_2) / P_1 \quad (12.2)$$

$$\text{or } \frac{Q_1}{Q_2} = \left( \frac{P_1}{P_2} \right)^{1/n} \quad (12.3)$$

where  $n$  is the power law index,  $Q_1$  and  $P_1$  are the rate and discharge pressure at condition 1, and  $Q_2$  and  $P_2$  are the rate and pressure at condition 2. The pressure at the die lip is assumed to be zero. For example, a 5% variation in the discharge pressure ( $\Delta P = 0.05$ ) for a polymer with a power law index of 0.3 will cause a 16% change in the instantaneous rate ( $\Delta Q = 0.16$ ). An instantaneous rate change of this magnitude is unacceptable for most processes. The flow relationship with pressure is much more complicated than this for a commercial die, but the trend is the same.

## ■ 12.2 Troubleshooting Flow Surging Processes

The analysis and troubleshooting of a process that is flow surging can be a difficult task, especially when the line is required to run production. The analysis can often be complicated by the operation of equipment downstream from the die. For example, if a pulling system is not operating at a constant speed then variations in velocity can cause the product to vary in dimension even though the extruder is operating stably. Worn components on a calendering roll stack can cause the speed of the rolls to vary or cause the gap between the rolls to change during a revolution. Both conditions will cause the product to change dimensions in the downstream direction. Unit operations downstream from the die must be checked to determine if they are the root cause of the product variation. The troubleshooter must be diligent to set a hypothesis and then test the hypothesis. If some problem other than the root cause is fixed, then the process will continue to flow surge.

The standard array of diagnostic equipment is required for the troubleshooting of a process that is flow surging. These tools include screw measuring devices, pyrometers, and devices to calibrate sensors in the process. These devices are discussed in Chapter 10. Often it is very difficult to impossible to determine a cause and effect relationship from process displays that are attached to typical extrusion

lines. However, a portable data acquisition system that is capable of collecting process data as a function of time is highly useful in determining the cause and effect relationships between process parameters. In all of the cases presented here, the extrusion line was either equipped with a data acquisition system or a temporary acquisition system was connected to the machine during the trial.

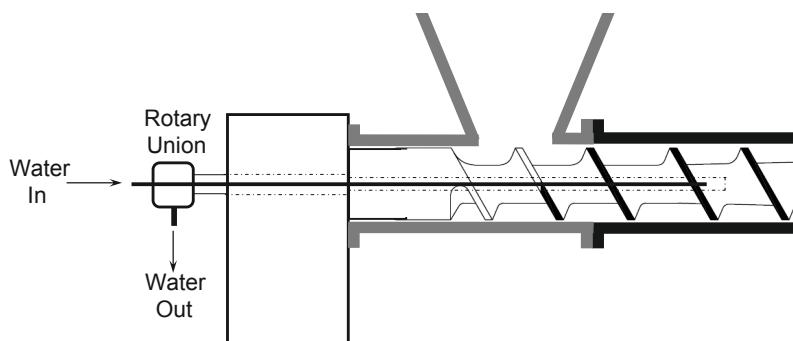
## ■ 12.3 Barrel Zone and Screw Temperature Control

Improper selection of process temperatures, poor temperature control, and inoperative temperature control devices are common causes for flow surging. As stated earlier, temperatures for the metal surfaces in the solids-conveying zone must be within a specific range for an application. This temperature range will depend on the resin, equipment design, placement of the temperature control sensor, and rate. Thermocouple placement on extruders is not standard, and thus they can be positioned at different axial positions for the zones and at different depths into the barrel wall. Because of these extruder and process differences, barrel temperatures typically need to be optimized for the machine and application. Optimization of barrel temperatures was presented in Section 10.9.

Equipment devices that are not functioning properly can cause a process to flow surge. For example, the feed casing of the extruder is typically cooled with water such that the outside temperature of the casing is about 50 °C or less. If the cooling water flow is turned off or is not flowing at a high enough rate, then the temperature of the inside wall of the casing will become too hot to convey solids into the machine. As a general rule for most resins, the outside temperature of the feed casing will be too hot to touch if the inside wall becomes too hot to convey solids, that is, at temperatures higher than 50 °C. At high casing temperatures, the rate-limiting step of the process is the solids conveying of resin from the casing to the barrel and not the metering channel of the screw. Thus, the specific rate will decrease and flow surging is very likely to occur. For specialty PE resins with very low solid densities, the temperature of the feed casing may need to be less than 35 °C. High temperatures on the feed casing can also cause the resin to bridge over the feed opening such that pellet flow to the extruder is severely or completely restricted.

Flow surging can occur if the temperature of the screw becomes too high in the solids-conveying section. In general, the temperature of the screw in this section needs to be less than the  $T_g$  for amorphous resins or less than the melting temperature for semicrystalline resins. Small-diameter screws will typically operate at feed

zone screw temperatures that are low enough without the need for special cooling. For screws 150 mm in diameter and higher, the temperature of the screw, however, can become too hot for optimal solids conveying. In these cases, the temperature of the screw can be decreased by flowing water into the screw using a rotary union and piping assembly, as shown in Fig. 12.1. Cool process water flows through the union and into a pipe that extends up to within 10 cm of the end of the cooling hole. The water then flows back out of the screw through a section of cast pipe. The cast pipe is attached by threads to the screw shank and rotary union. The length of the cooling hole and the flow rate of water are used to maintain the screw temperature in an optimal range. In general, the cooling hole is drilled into the screw up to the end of the feed section. Two case studies are presented that show flow surging processes that had poor temperature cooling on the feed section of the screw.



**Figure 12.1** Diagram showing a rotary union piping assembly for cooling the feed section of a screw

Two-zone temperature control of the screw has been utilized to mitigate process instabilities in the solids-conveying zone and carbonaceous material buildup on the screw root in the melting zone for polyvinylidene chloride (PVDC) resins [9]. Two-zone screw temperature control can also be used to control the temperature of the solids-conveying zone and energy removal in the metering zone. The control device is similar to that shown in Fig. 12.1 except that a second rotary union is required for the second fluid and a sealing device [10] is needed to isolate the cooling fluids.

### 12.3.1 Water- and Air-Cooled Barrel Zones

Heating and cooling of the barrel zones is typically done using modules that are equipped with electrical heaters and either water or air cooling. These modules are then clamped onto the outside of the barrel. Water cooling has the capability of removing more energy from the process, and it is well suited for extruders larger

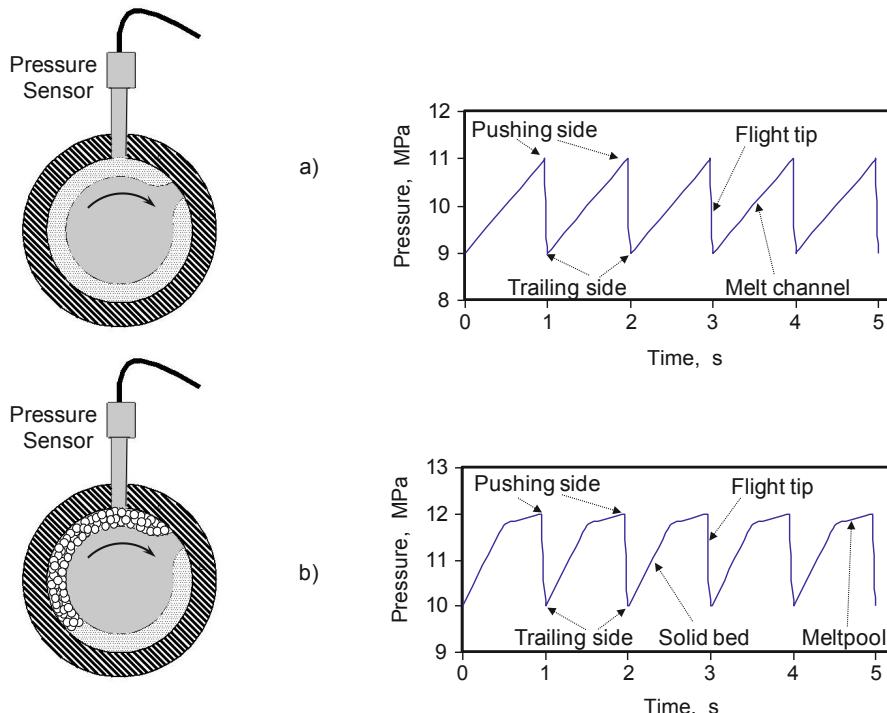
than 150 mm in diameter where the cooling demand is high, that is, where water flows to the modules for 10% or more of the time. If lower levels of cooling are required, however, water cooling can create temperature oscillations in the zone. For example when the zone becomes too hot, the controller will open the solenoid valve to the water flow line for the shortest possible duration. If this minimum amount of water flow is too large, then the cooling on the zone can be too much, causing the temperature of the zone to undershoot the set point temperature [11]. The control scheme will cause the zone temperature to oscillate. Variation in temperature for the barrel zones can affect the rate and discharge temperature. The oscillations can be mitigated by installing metering or needle valves in the water flow lines to reduce the water flow rate to the module. An in-line water filter is typically installed in the cooling line so that the needle valves do not get plugged with particulates.

Air-cooled zone modules do not have the ability to remove as much energy as do water-cooled units. For processes that only require a low level of cooling, air-cooled units will provide a more stable control of the temperature. Recent innovations in air cooling using high-flow fan systems [12] have allowed the replacement of some water-cooled systems with less costly and lower maintenance air-cooled systems [11].

## ■ 12.4 Rotation- and Geometry-Induced Pressure Oscillations

Pressure transducers that are positioned in the barrel can be extremely useful for troubleshooting a process. Common positions include midway into the melting section and at the entry to the metering section. For two-stage screws, positioning of a transducer at the entry to the second-stage metering section provides information on the degree of fill of the stage and provides knowledge on the likelihood of vent flow. The pressures measured from these transducers provide three types of information: (1) the average pressure in the channel, (2) the pressure variation in the angular direction due to the rotating screw, and (3) the stability of the process by comparing the pressure oscillations during several screw rotations. The pressure in the angular direction is composed of two pressure components: (1) a pressure component in the downstream direction,  $\partial P / \partial z$ , and (2) the cross-channel pressure gradient,  $\partial P / \partial x$ . The shape of the angular pressure profile depends on the magnitudes of the components. In order to measure the pressures during rotation, high-speed data acquisition equipment is required. For example, a screw that is rotating at a speed of 60 rpm will require a data acquisition frequency of at least

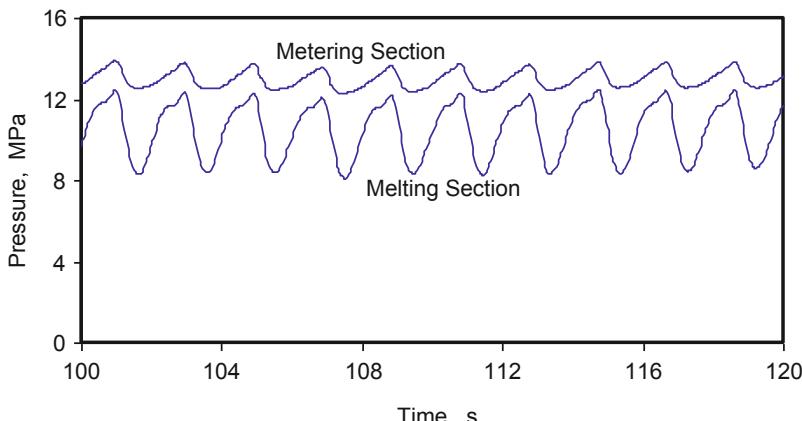
20 Hz, providing 20 pressure measurements per rotation. Typical pressure measurements for transducers positioned in melting sections and metering sections that are filled with molten resin are shown in Fig. 12.2.



**Figure 12.2** Typical pressure measurements for transducers positioned in the barrel for a screw speed of 60 rpm and a positive downstream pressure gradient ( $\partial P / \partial z > 0$ ):  
 a) for a transducer positioned in a metering section where the resin is completely molten, and  
 b) for a transducer positioned in a single-flighted melting section

The pressure profile shown in Fig. 12.2(a) is for a constant-depth metering channel that is completely filled with molten resin, a screw speed of 60 rpm, and a positive downstream pressure gradient ( $\partial P / \partial z > 0$ ); five rotations are shown. The pressure is the highest at the pushing side of the channel and the lowest at the trailing side of the channel. The pressure typically increases nearly linearly with rotation from the trailing side of the channel to the pushing side. As the flight tip passes underneath the transducer, the pressure decreases quickly to that of the trailing side of the channel. Figure 12.2(b) shows a similar pressure profile with rotation in a conventional melting section. For this case, the solid bed extends across about 50% of the channel. The pressure profile is similar to that for the metering channel case except that the pressure gradient in the region over the solid bed is higher than that for the melt pool. The width of the molten resin can be estimated by the time fraction that the transducer spends over the melt pool and solid bed.

The pressure profiles with rotation shown in Fig. 12.2 are ideal. In practice the pressure profiles contain a level of measurement error and unsteady-state behavior. Pressure in an actual channel operating at a screw speed of 30 rpm for an ABS resin is shown in Fig. 12.3.



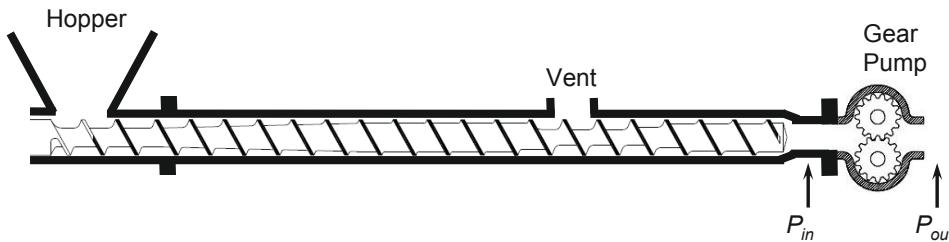
**Figure 12.3** Measured pressure profiles with rotation for a 63.5 mm diameter extruder running an ABS resin at 30 rpm, a conventional single-flighted screw, and with a positive downstream pressure gradient in the metering section ( $\partial P / \partial z > 0$ )

As shown in Fig. 12.3 for the metering channel, the highest pressure is at the pushing side of the channel and the lowest is at the trailing side of channel. The angular pressure profile in the melting section was typical and very similar to the ideal profile shown in Fig. 12.2 because properly operating melting sections have positive pressure gradients in the downstream direction. The data in Fig. 12.3 clearly shows that a level of measurement noise and unsteady-state activity is occurring in the process.

## ■ 12.5 Gear Pump Control

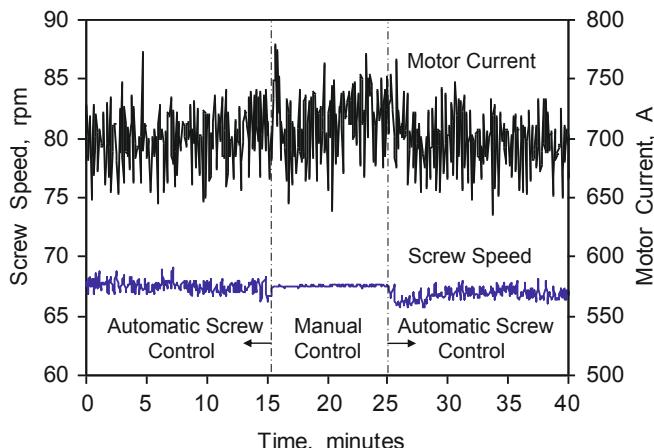
Gear pumps are often positioned between the extruder and the die, and they provide several processing advantages. These advantages include the mitigation of pressure and flow surges from the extruder, a decrease in the discharge temperature by generating the pressure for the die by the pump instead of the extruder, and by decreasing the discharge pressure via the pump, a capacity increase is possible [13]. For gear pump assisted extrusion, the extruder control algorithms are set to maintain a constant pressure to the inlet side of the pump. The pump is operated at a constant rotational speed, and thus it delivers molten polymer at a very steady and controlled rate. A schematic of a gear pump assisted extrusion

process is shown in Fig. 12.4. If the pressure to the inlet of the pump is less than the set point value, then the control system will increase the screw speed of the extruder. Conversely, if the inlet pressure is too high, the control system will decrease the screw speed. Thus, processes that use a gear pump downstream of an extruder can show large variations in the screw speed in an attempt to compensate for an extruder that is flow surging.

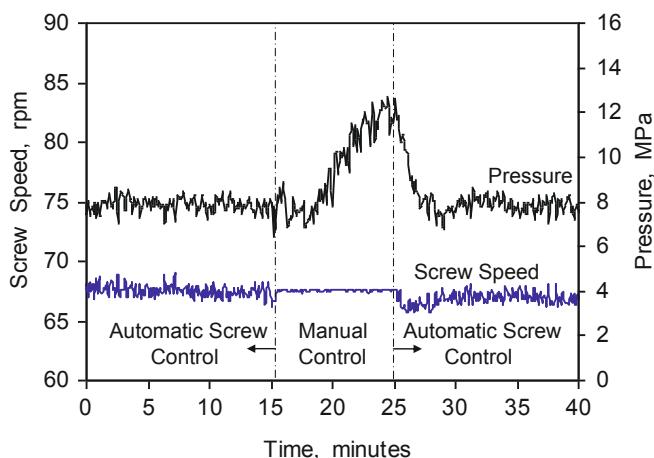


**Figure 12.4** Schematic of a two-stage extruder with a downstream gear pump

A poor control algorithm for the pump can cause some variation in the extruder screw speed, causing large variations in the inlet pressure to the pump. This type of control-induced surging can occur even though the process as designed is inherently stable. To determine if the control algorithm is inducing the surging, the screw speed of the extruder should be operated in a manual mode and at a constant speed. If the controller is inducing the surging, placing the process in manual-control mode will stabilize the process. Transient process data were collected for an extruder with a downstream gear pump, as shown in Fig. 12.4. For this case, the control algorithm was controlling the speed of the screw such that the inlet pressure to the pump was maintained at 8 MPa. Although the variation in screw speed was not excessive at  $67 \pm 1.5$  rpm, the variation in motor current seemed quite high at  $540 \pm 90$  A. At about 16 minutes into the run, the extruder was switched from automatic to manual screw control; the screw speed was held constant at 67 rpm. As shown by the data in Fig. 12.5, the motor current variation was unchanged, indicating that the screw speed control algorithm was not inducing the variation in the motor current. During the period that the screw speed was held constant, the pressure to the inlet of the pump slowly increased, as shown in Fig. 12.6. This pressure was increasing because the screw was operating at a speed that delivered a rate slightly higher than that needed by the pump. When the control was placed back into automatic mode, the screw speed was decreased initially to compensate for the higher than desired inlet pressure. This type of analysis is recommended when minor levels of flow surging are observed with a process where the screw speed is controlled from the inlet pressure of a gear pump.



**Figure 12.5** An extrusion process with a downstream gear pump with the screw operating in inlet pressure control and followed by the screw in manual operation (constant screw speed). The large level of variation in the motor current during constant screw speed control suggests that the extruder process is unstable, and the control algorithm is not the root cause for the variation in the motor current



**Figure 12.6** Pressure at the inlet to the gear pump for the data presented in Fig. 12.5. The pressure increased during manual control because the flow rate of the extruder was slightly higher than the rate of the pump

## ■ 12.6 Solids Blocking the Flow Path

Compacted solid polymer fragments can block and restrict the flow in a process. In order for this to occur, two defects typically exist in the process. The first defect causes the compacted solid to fragment and flow downstream in the screw channels. The second defect is a restriction in the channel where the fragments are trapped and accumulated. As the restriction builds, the local pressure just upstream of the restriction will increase while the pressure downstream will decrease. As the downstream pressure decreases, the pressure and rate at the discharge of the extruder will also decrease. The local and high pressure just upstream of the restriction will cause the melting rate of the fragments to increase, temporarily clearing the blockage [2]. When the blockage is removed the rate of the process returns to normal until the next solid fragment blocks the restricted region. Repeated blocking and clearing of the restricted region creates the flow surging.

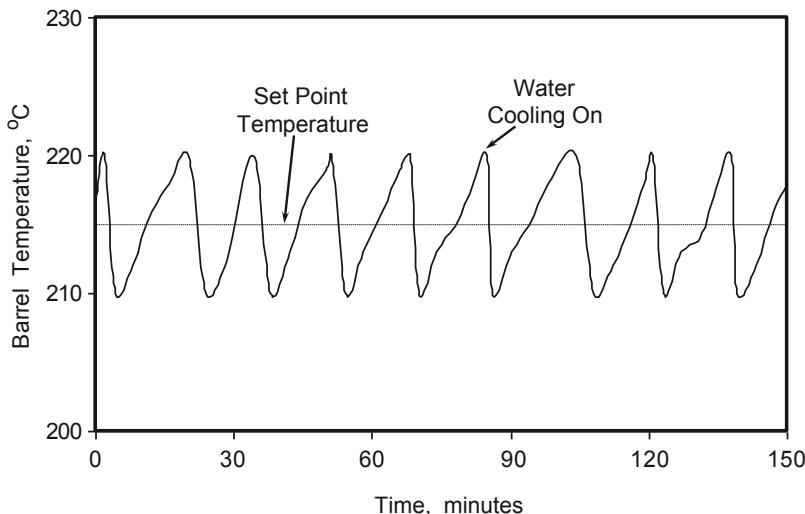
To eliminate surging due to solid blockages, the troubleshooter must eliminate the defect that caused the solid bed to break up and must also mitigate the restriction in the downstream section of the screw. It is preferred to correct both defects to permanently eliminate surging from the process.

## ■ 12.7 Case Studies for Extrusion Processes That Flow Surge

Numerous case studies are presented in the next sections that show some common flow surging problems. In these case studies, the problem is presented in a manner that the troubleshooter would encounter during a trial or information-gathering session. Incomplete data and erroneous data are often presented to the troubleshooter. These data were not included here because including them may mislead the reader. The troubleshooter, however, must be able to separate the actual facts of the process from misleading perceptions. In each case study, the modifications required to fix the process are detailed along with supporting fundamental information. In all cases, the rate of the process was limited and the cost to manufacture was high.

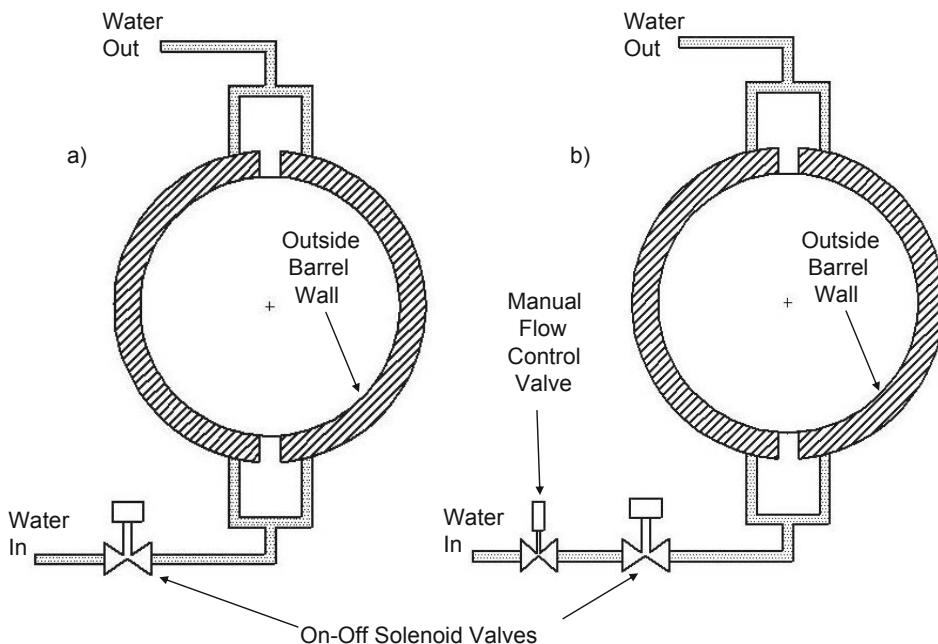
### 12.7.1 Poor Barrel Zone Temperature Control

A 203.2 mm diameter plasticating extruder was running GPPS resin and discharging to a specialty downstream process. Like most processes, the downstream equipment required a nearly steady supply of molten polymer. For this case, the



**Figure 12.7** Barrel temperature data for a 203.2 mm diameter extruder running GPPS resin and with water cooling on the barrel heating and cooling. This extruder was configured with a water-cooling capability that was too high for the process

barrel zones were electrically heated and water cooled. The barrel zone temperature is shown in Fig. 12.7. The barrel heater for this zone was only used during startup. Once the extruder was operating, the energy dissipation from the screw to the resin was more than enough to keep the section hot. In fact, in order to maintain the zone at the set point temperature of 215 °C, the extruder was operated with a very small amount of barrel cooling. At the low-temperature portions of the cycle, both heating and cooling were off. The small amount of excess energy dissipated in the screw channel was causing the barrel temperature to increase slightly with time. When the temperature exceeded 220 °C, the control algorithm took action and opened the solenoid valve on the water line upstream of the heating and cooling barrel jacket, as shown in Fig. 12.8(a). The controller opened the solenoid valve for the minimum amount of time, sending a short burst of water to the zone. The water would flash evaporate in the unit and then quickly cool the barrel to about 210 °C. Since the solenoid was opened for the shortest possible amount of time, the level of cooling that was utilized was the minimum. It was very obvious that the level of cooling water to this barrel zone was too high for this process. The barrel temperature oscillations shown in Fig. 12.7 were enough to cause a small variation in the product dimensions. Although the variations in the product dimensions were acceptable, the variations did reduce the profitability of the process by causing too much resin to be used in the final product.



**Figure 12.8** Heating and cooling system on the barrel: a) schematic of the original configuration that created the temperature oscillations in Fig. 12.7 and b) a better configuration that minimized the temperature oscillations

In order to reduce the cooling level to the barrel zone, a metering valve was placed in the water line upstream of the solenoid valve as shown in Fig. 12.8(b). Now when the controller opens the solenoid valve, a much lower quantity of water and thus cooling is available to the barrel zone. Prior to this modification, the barrel temperatures oscillated  $\pm 10^\circ\text{C}$  about the set point temperature. After the modification, the temperature oscillations were reduced to about  $\pm 3^\circ\text{C}$ , and the profitability of the process was improved due to the minimization of resin consumption.

This temperature control problem occurred due to the implementation of a high-performance-type screw. The original screw was fabricated with a relatively shallow metering channel. The shallow channel had a low specific rate and also dissipated a relatively high level of energy. The excess energy was easily removed through the barrel wall with the water cooling using the configuration shown in Fig. 12.8(a). That is, the solenoid valve was in the open position enough to maintain cooling while not causing the barrel temperature to undershoot the set point temperature. The high-performance screw, however, was designed with a deeper metering section, had a considerably higher specific rate, and dissipated less energy. For this screw, less excess energy needed to be conducted through the barrel wall. Since the cooling system was designed for a process with a high heat flux through the barrel, the temperature became very oscillatory when the energy flux was reduced when the high-performance screw was implemented.

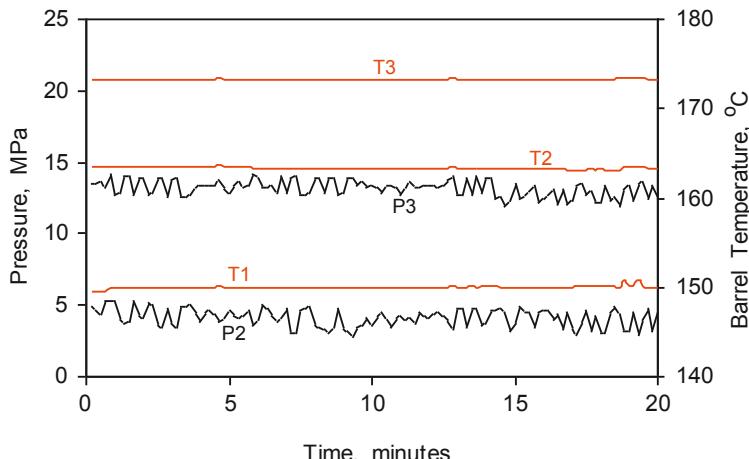
This simple case study shows the importance of verifying the control algorithms before proceeding with a troubleshooting trial. Before any testing or equipment modifications are performed, it is extremely important to have a deep understanding of the process and have all process controls and sensors in acceptable operation. If the sensors and controls are not functioning properly, then the troubleshooter may modify the wrong section of the process and obtain little to no improvement in the process.

### 12.7.2 Optimization of Barrel Temperatures for Improved Solids Conveying

Numerous complaints were logged by a single processor from several different manufacturing plants on flow surging and reduced rates for a specialty resin. The flow surging caused unacceptable variations in the final product. In all cases small-diameter extruders were used, but the operating conditions reported were different in the plants. In several of the plants, there were some extruders that did not flow surge, yet the design of these machines appeared to be identical to those that experienced flow surging. It was not apparent why some of the extruders were operating well while others were surging.

An extrusion trial was performed at the processor's plant using a 38.1 mm diameter production extruder, a proprietary screw design, and resin that had previously exhibited flow surging and reduced rate. The extruder was equipped with three barrel zone heaters with control thermocouples (labeled T1, T2, and T3) and two pressure sensors. One pressure sensor was located in the midsection (zone 2) of the barrel (P2) and the other at the end of the barrel near the tip of the screw (P3). Both transducers were positioned over the top of the screw such that a pressure variation due to screw rotation would be observed.

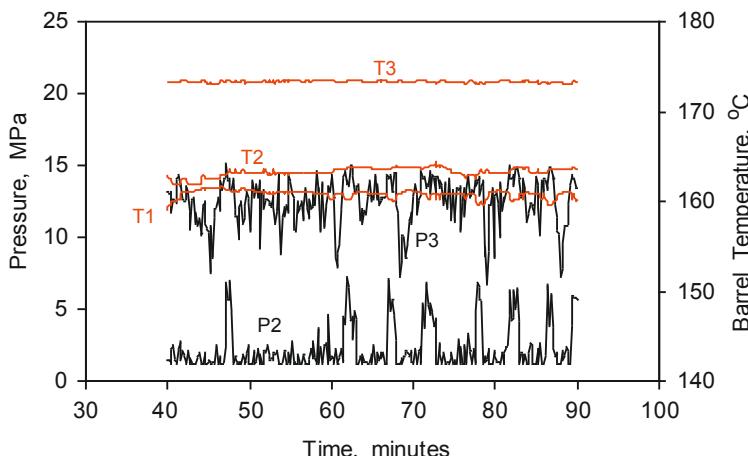
During the trial, process data were collected from each sensor at a frequency of once every 10 seconds using a portable data acquisition system. For barrel zone temperatures of 150, 163, and 174 °C for zones T1 through T3, respectively, the extruder was operating stably and at rates that were consistent with numerical simulations, and it was producing a high-quality product. Process data for steady-state operation are shown in Fig. 12.9 for a screw speed of 50 rpm. As indicated by this figure, the barrel zone temperatures were steady and only small variations occurred for the P2 and P3 pressure sensors. Slight pressure variations were expected for this extruder because the sensors were positioned in the barrel and were measuring pressure in different regions of the channel as the screw rotated. The pressure patterns are not periodic like those in Fig. 12.3 due to the screw speed and acquisition rate used. For this case, pressure samples were collected every 8.3 rotations. A faster data collection rate would have shown a periodic oscil-



**Figure 12.9** Barrel pressures and temperatures for the 38.1 mm diameter extruder operating stably. The temperature profiles are in red while the pressures are black

lation of the pressure. These data indicate that conditions exist for the stable processing of the resin.

For a second experiment, the extruder was operated at barrel set point temperatures of 160, 163, and 174 °C for zones T1 through T3; the zone T1 temperature was increased by 10 °C, and zones T2 and T3 temperatures were unchanged. This increase in the T1 temperature caused the extruder to flow surge and decreased the rate by about 20 %. The process data for the unstable conditions are shown in Fig. 12.10. As indicated by this figure, the pressure for the midbarrel pressure sensor, P2, was zero during the low pressure swing of the cycle, indicating that this portion of the channel was operating partially filled (or starved). Later in the experiment, the pressure sensor responses were checked when the pressure was known to be zero in the channels. The pressure was measured by the sensors at 1.4 MPa when the pressure was actually zero, explaining the offset pressure at the bottom of the pressure cycle in Fig. 12.10. Numerical calculations and a Maddock solidification experiment confirmed that the midsection of the extruder was operating partially filled. Thus, a small 10 °C increase in the first barrel zone temperature was enough to cause the extruder to go from operating as a stable process producing high-quality product to one that was unstable with reduced rates and having a product with unacceptable product dimensions. Numerous other experiments had shown that the first barrel zone temperature needed for stable extrusion depended on the screw speed and the temperature of the feed resin. Moreover, the processor indicated that flow surging was experienced for some extruders at zone T1 barrel temperatures as low as 148 °C.



**Figure 12.10** Barrel pressures and temperatures for the 38.1 mm diameter extruder operating at a zone 1 barrel temperature condition that caused the extruder to flow surge. The temperature profiles are in red while the pressures are black

Based on the data collected, the Maddock solidification experiment, and the numerical calculations, the problem was diagnosed as poor solids conveying from improper temperatures in the section. Slight differences between extruders, such as the axial and radial position of the zone T1 thermocouple, barrel zone controller tuning, screw geometry variations, and thermocouple accuracy likely caused conditions such that some of the extruders flow surged while others did not. These minor variations could influence the temperature of the inside barrel wall of the solids-conveying section. Moreover, different rate requirements for different products required that the extruder be operated at different screw speeds, which further complicated the solids-conveying problem. The problem could have been avoided if plant personnel had optimized the barrel temperatures for each extruder using the technique described in Section 10.9.

### 12.7.3 Flow Surging Due to High Temperatures in the Feed Section of the Screw

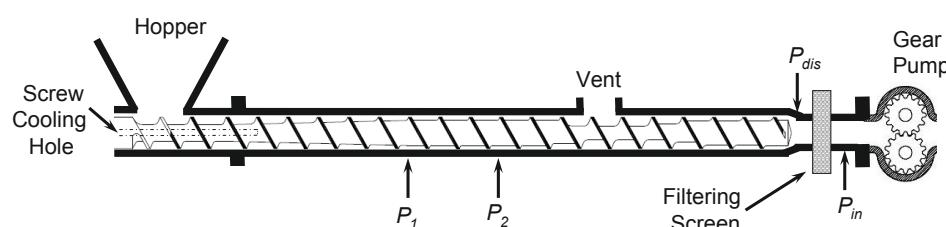
A severe and random flow surging problem limited the production rate for a large-diameter, two-stage, vented extruder. If it were not for a gear pump positioned between the extruder and die, this extrusion line would not have been operable. The surging did, however, limit the output of the line to about 70% of its potential rate. The maximum potential rate is the rate that the extruder can run at high screw speeds and with proper operation. The extruder was 203.2 mm in diameter and had a 40  $L/D$  barrel. A schematic for the extruder and gear pump arrangement is shown in Fig. 12.11, and the screw channel dimensions are provided in

Table 12.1. The specific rotational flow rate for the first-stage metering section was calculated at 20.0 kg/(h·rpm). The extruder was fed a mixture of fresh HIPS resin with 30 to 60% recycled ground sheet from a downstream thermoforming process. The level of recycle affected the bulk density of the feedstock entering the extruder. The HIPS resin had an MFR of 3.9 dg/min (230 °C, 5.0 kg). The screw was single-flighted and typical of what is used for HIPS resins. Screw temperature control was accomplished by flowing cooling water through a rotary union into and out of a hole cut into the feed end of the screw as shown in Fig. 12.1. This hole extended 3.8 diameters into the feed section. Pressure sensors were positioned in the barrel wall at the end of the first-stage transition section (P1), at the end of the first-stage metering section just before the vent (P2), and at the discharge. Additional pressure sensors were positioned at the discharge of the extruder and at the inlet (suction side) to the gear pump. A screen filtering system was positioned between these pressure sensors as shown in Fig. 12.11. A commercial control scheme adjusted the screw speed to maintain a constant pressure of 9 MPa to the inlet of the gear pump. The gear pump was operated at constant speed in order to maintain a constant flow rate of material to the die.

**Table 12.1** Screw Channel Dimensions for a 203.2 mm Diameter Two-Stage Vented Screw Running HIPS Resin

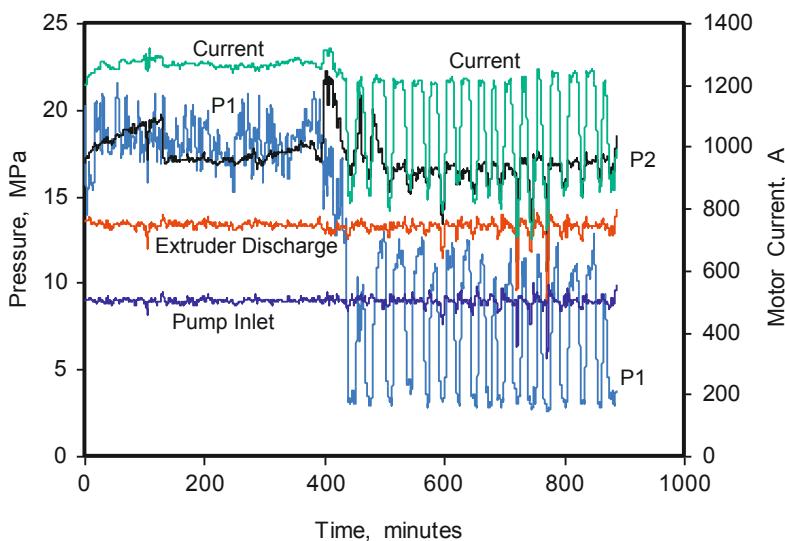
	Depth, mm	Length, diameters	Notes
Feed section	28.6	7	
First-stage transition		10	
First-stage meter	7.1	8	
Vent section	31.9	4.5	The pump ratio was 1.7
Second-stage transition		3.5	
Second-stage meter	12.3	6	

Lead length, flight width, and flight clearance were 203.2, 23.9, and 0.20 mm, respectively, in all sections of the screw. A 28.7 mm diameter screw cooling hole was drilled in the shank end of the screw, and it extended 3.8 diameters into the feed section. The first 2.5 diameters of the screw were inside a water-cooled feed casing. The specific rotational rate of the first-stage metering section was calculated at 20 kg/(h·rpm).

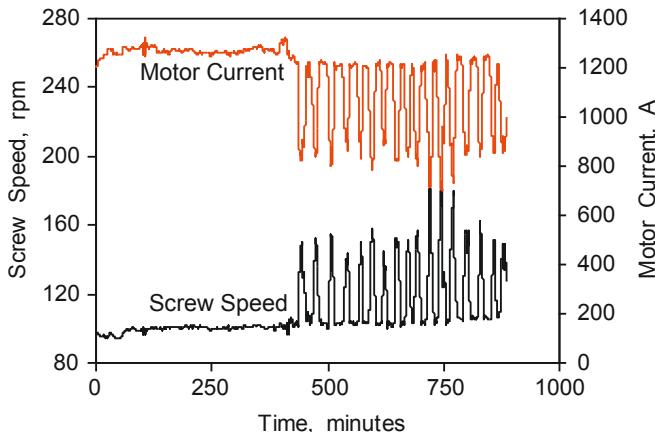


**Figure 12.11** Schematic of the 203.2 mm diameter extrusion process for HIPS resin

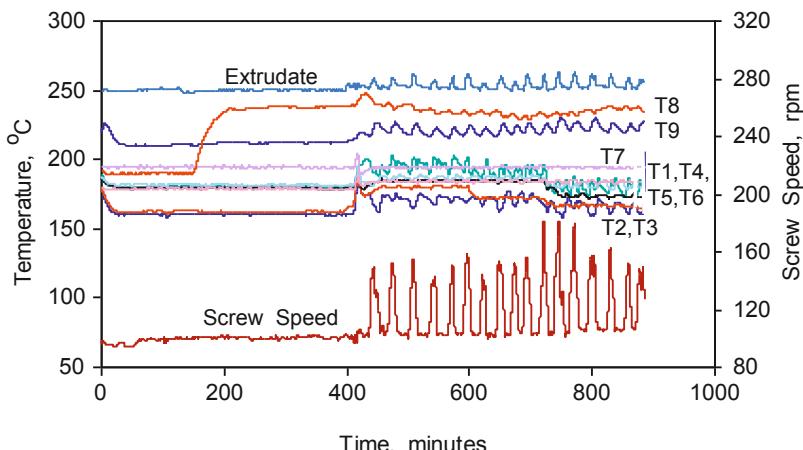
In order to diagnose the problem, a data acquisition system was temporarily connected to the extrusion panel. All available sensor outputs were connected in parallel with the acquisition system. Electronic data were collected at a frequency of once every 9 s. Steady-state operation of the extruder is shown by the first 400 minutes in Figs. 12.12, 12.13, and 12.14. The data for these figures were from the same production run. The extruder was running at 2250 kg/h and a screw speed of 99 rpm for a specific rate of 22.7 kg/(h·rpm). This specific rate is about 14% higher than the specific rotational flow rate calculated for the first-stage metering section, indicating that a negative pressure profile exists in the section. The negative pressure gradient is expected for a first-stage metering section of a vented screw that is operating properly; that is, the first-stage metering section was full of resin. To maintain the stability, the extruder screw speed was reduced such that the extruder was operating at about 70% of its potential maximum rate. That is, at screw speeds higher than 99 rpm the extruder was more likely to transition from a stable to an unstable operation. The barrel pressure at the end of the first-stage transition section, P1, had variations of about  $\pm 3$  MPa about the average pressure. This pressure variation was considerably higher than expected and suggests that the extruder, although running stably, was on the verge of unstable operation. Some of the variation was due to the movement of the flight tip past the sensor. Barrel zone temperatures tracked the set point values and were stable.



**Figure 12.12** Barrel, discharge, and pump inlet pressures and motor current for stable and unstable extrusion for a large-diameter extruder running HIPS resin



**Figure 12.13** Screw speed and motor current for a large-diameter extruder running stably and unstably



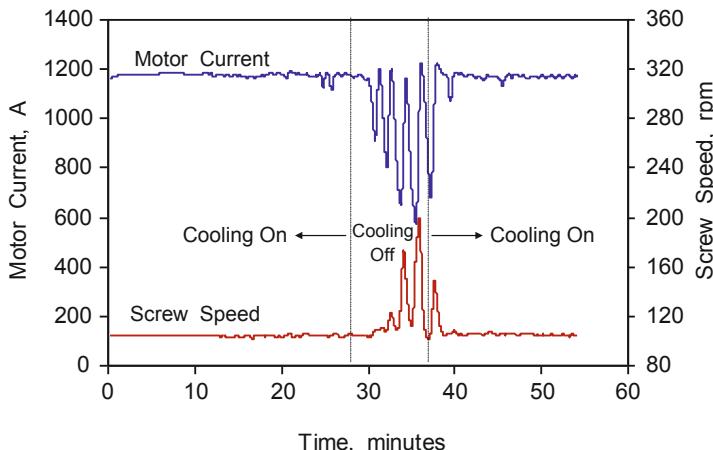
**Figure 12.14** Screw speed, extrudate temperature, and barrel zone temperatures for a large-diameter extruder running stably and unstably

At about 410 minutes into the run, the extruder started to operate unstably, as indicated in Figs. 12.12, 12.13, and 12.14. The processing change that caused the extruder to go from a stable operation to an unstable one was not known, but it could have been due to minor changes in the bulk density of the feedstock or cooling water fluctuations to the screw. As indicated by these figures, the event started when the P1 pressure decreased slightly, causing the rate and the P2 pressure to decrease. This decreased pressure transmitted down the extrusion system, eventually decreasing the pressure at the inlet to the gear pump. To correct for the lower pressure, the controller on the gear pump increased the speed of the screw from 99 rpm to about 160 rpm. Next the P1 pressure increased due to the higher

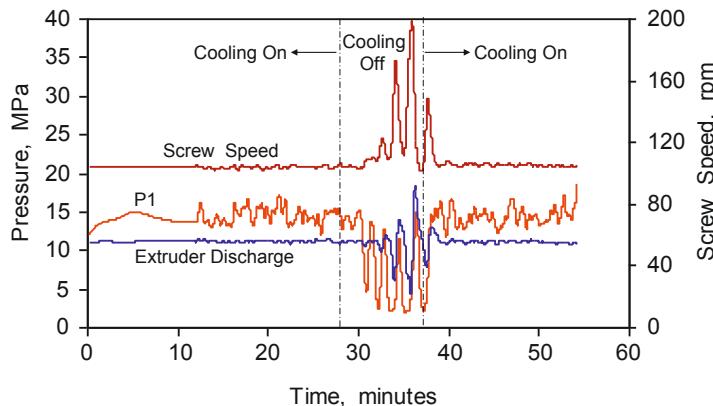
screw speed and higher flow rate, as indicated in Fig. 12.12. As the pressure increased at the gear pump inlet, the gear pump controller decreased the screw speed back to about 100 rpm, causing the extruder to flow surge. Flow surging caused the screw speed controller to oscillate about once every 25 minutes. As indicated in Fig. 12.12, the screw speed controller was able to provide a relatively stable pressure to the pump inlet, allowing the process to run at reduced rates. The barrel zone temperatures, as indicated in Fig. 12.14, were extremely oscillatory.

As indicated in Fig. 12.12, the P1 pressure was considerably lower during the period of unstable operation. This result indicates that the cause of the problem originated in the first stage of the screw before the first-stage metering section. At a screw speed of 160 rpm, the extruder was still operating at a rate of 2250 kg/h, but the specific rate decreased to 14 kg/(h·rpm). This specific rate is considerably less than the specific rotational flow rate of 20 kg/(h·rpm), indicating that the first-stage metering section was operating improperly and only partially filled. The most likely reason for a partially filled or starved metering section was poor solids conveying from the feed section to the transition section. Poor solids conveying was likely due to improper temperature control of the metal surfaces in the feed section of the extruder and screw. Barrel feed zone heaters, controllers, and the feed casing were examined and determined to be operating properly at set point temperatures typically used for HIPS resin. Based on this information, the investigation was focused on the temperature control of the screw.

It was hypothesized that the screw temperature in the feed section was too hot to convey solids effectively to downstream sections of the screw. To test this hypothesis, the effect of internal screw cooling was determined during a period when the extruder was operating stably. For this period, cooling water was flowing to the screw-cooling device, and the extruder was operating stably and properly at a rate of 2360 kg/h and a screw speed of about 104 rpm. The metal surface temperatures of the pipes used to flow water into and out of the screw were measured at 29 and 37 °C, respectively. At about 28 minutes into the run, the cooling water flow to the screw was turned off, as indicated in Figs. 12.15 and 12.16. At about 30 minutes, the pressure at the end of the first-stage transition section, P1, started to decrease as shown in Fig. 12.16, indicating that solids conveying was significantly reduced. Like before, the reduced solids flow caused the downstream pressures to decrease and ultimately to cause the extruder to flow surge. At about 36 minutes into the run, cooling water flow was turned on, and within about four minutes the extruder operation became stable, as indicated in Figs. 12.15 and 12.16. The surface temperature of the pipe for water flow out of the screw was measured at 81 °C just after the cooling water was turned on, a temperature change of 44 °C. As will be presented later in this section, solids conveying of HIPS resin becomes difficult or unstable at screw temperatures of about 150 °C and higher. The temperature of the screw surface was unknown, but it likely increased by at least 44 °C and possibly approached 150 °C.



**Figure 12.15** Screw speed and motor current for the screw cooling experiment



**Figure 12.16** Screw speed, pressure at the entry to the first-stage meter (P1), and discharge pressure for the screw cooling experiment

Based on the above data, the cause of the extrusion instability was identified as high temperatures on the screw surfaces of the feed section. These high surface temperatures caused the coefficients of dynamic friction to increase, increasing the retarding forces on the solids at the screw surface. Since solids conveying depends on a combination of forwarding forces at the barrel wall and pushing flight and retarding forces at the screw root and trailing flight, an increase in the retarding forces will cause a reduction in the solids-conveying rate. The instability appeared to be random due to the complicated interactions of cooling water flow rate and temperature and due to changes in bulk density of the feedstock.

Several technical solutions were considered to increase the cooling level to the feed section of the screw, including increased water flow and the use of chilled water. The best technical solution and quickest to implement was to increase the

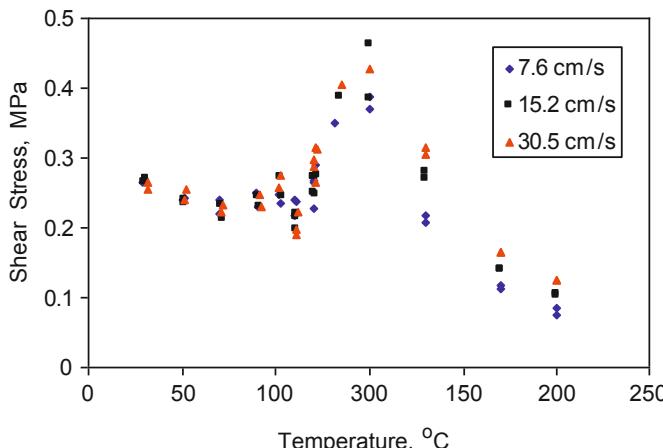
length of the cooling hole in the screw. The length of the cooling hole was increased from 3.8 diameters into the flighted section to 7 diameters up to the end of the feed section. After the screw modification, the extruder has not experienced instabilities of this type, and the rate has increased to 100 % of its maximum potential rate.

Cooling on the screw and feed casing are often limited by the water pressure at the supply and discharge sides. That is, if the water pressure on the discharge header is nearly the same as that of the supply side, then the water flow rate will be very low due to the lack of a pressure driving force. Thus, if the driving pressure for water flow is not available then adequate cooling to the screw and casing may not exist. A simple way to test if the cooling water flow is acceptable is to disconnect the discharge water line from the header and either flow this water to a drain or the parking lot using a temporary hose. The discharge water flow should be high and the temperature should be warm to the touch. A permanent arrangement might consist of a water pump and a rotameter in-line upstream of the rotary union attached to the screw.

To aid in the understanding of this solids-conveying problem, the coefficient of dynamic friction was measured for the resin as a function of temperature and sliding velocity at a pressure of 0.7 MPa. The equipment used to make the measurement is described in Section 4.3.1 and is shown in Fig. 4.11. Since the coefficient of dynamic friction is only defined for solid-state processes, the friction values are reported here as stress at the interface because the stress can be described from ambient temperatures up to processing temperatures. The shear stress at the interface for HIPS resin is shown in Fig. 12.17 at a pressure of 0.7 MPa. As indicated by this figure, the shear stress was nearly constant from ambient temperature up to about 110 °C, increased to a maximum stress near 150 °C, and then decreased as the temperature was increased further. Optimal performance of the solids-conveying section for this resin would be such that the forwarding forces are maximized with metal surface temperatures near 150 °C where the stress is a maximum, and the retarding forces minimized with metal surface temperatures of 110 °C or lower. Thus, optimal solids conveying for HIPS resin would occur with a feed zone barrel inner surface temperature near 150 °C and a screw surface temperature in the feed section no higher than 110 °C. In practice, screw temperatures less than 90 or 100 °C are preferred such that melting of the resin does not happen if an emergency shutdown should occur. For the solid state temperature region, the shear stress at the interface can be converted to the coefficient of dynamic friction by the following:

$$f = \tau / P \quad (12.4)$$

where  $f$  is the coefficient of dynamic friction,  $\tau$  is the shear stress at the polymer-metal interface, and  $P$  is the pressure (0.7 MPa in this case).



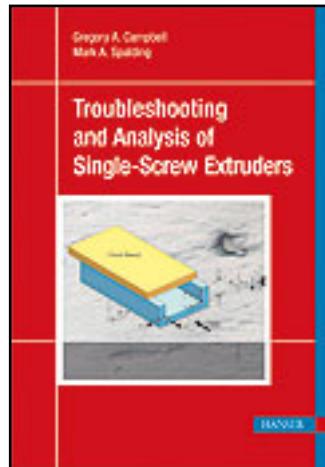
**Figure 12.17** Shear stress between HIPS resin and a metal surface at a pressure of 0.7 MPa and as a function of temperature and sliding velocity

#### 12.7.4 Flow Surging Due to High Temperatures in the Feed Casing

The extruder described in Fig. 12.11 on a different occasion started to flow surge but with a slightly different frequency, as shown in Figs. 12.18 and 12.19. As indicated in these figures, there were short time periods when the discharge pressure and screw speed were stable and the motor current was high. During these periods, the extruder was operating well but at a reduced production rate. During periods of unstable operation, the motor current decreased by about 20%, the screw speed increased, and the discharge pressure became extremely oscillatory. Like the previous case, as the motor current decreased solids conveying decreased, causing the controller to increase the speed of the screw.

During the trial, the feed casing to the extruder had an outside surface temperature of about 80 °C. Although not measured, the inside cylinder wall of the feed casing for the first 1.5 diameters downstream of the feed opening was considerably hotter. These higher temperatures were caused by a combination of frictional heating of the solids on the wall and also by conduction from the first heated zone of the barrel. It is estimated that temperatures as high as 170 °C occurred in the feed casing. As presented in Section 12.7.3, optimal solids conveying will occur when the stress at the polymer-metal interface at the barrel is a maximum, and for HIPS resin this surface temperature is near 150 °C. Surface temperatures higher than 150 °C in the feed section will reduce conveying and lead to starving of the screw channels and ultimately flow surging. Corrosion inside of the cooling channels of the feed casing prevented the flow of cooling water. Cleaning the cooling channels and adding a larger cooling water recirculation pump reduced the temperature of the feed casing and eliminated the flow surging problem.

# HANSER



## Stichwortverzeichnis

Gregory A. Campbell, Mark A. Spalding

Analyzing and Troubleshooting Single-Screw Extruders

ISBN (Buch): 978-3-446-41371-9

ISBN (E-Book): 978-3-446-43266-6

For further information and order see

<http://www.hanser-fachbuch.de/978-3-446-41371-9>

or contact your bookseller.

# Author

## A

Abrantes 117, 141, 705, 706, 708, 712, 713  
Adams 97, 98, 99, 100, 102  
Agassant 255  
Agur 132, 173, 279, 281  
Alemanskin 336  
Allen 53, 255  
Alotaibi 118  
Altinkaynak 119, 121, 152, 195, 197, 200, 212, 213, 445, 447, 574, 587, 601, 695  
Anderson 368, 369, 370, 371, 372, 373  
Angel 374  
Anolick 662  
Arcer 24, 51, 68, 70, 101  
Armeniades 368  
Armstrong 76  
Avenas 255  
Avérous 25  
Avgousti 228

## B

Baba 200, 226  
Baer 32  
Baird 132, 146, 147, 149  
Baker 377, 663  
Balch 257  
Balke 495  
Bar 486  
Barlow 438, 440  
Barr 6, 199, 225, 255, 365, 366, 367, 400, 419, 536, 575, 626, 635, 639, 641, 643, 645  
Beagan 332  
Benkreira 333, 346, 347, 374, 523  
Berghaus 174  
Bernhardt 303  
Berry 101  
Biesenberger 662  
Bigio 337, 353, 498, 515, 662  
Billham 379  
Bird 76, 261  
Black 332, 333  
Blackson 486

Bohn 151  
Bokis 661, 671  
Bomma 338  
Booy 256  
Boussinesq 255, 744  
Boyd 353  
Bozzelli 238, 374  
Bremner 377  
Brittin 374, 523  
Brizzolara 662  
Brown 661, 671  
Broyer 92, 139, 142  
Bruin 257  
Bruker 257, 258  
Buchelli 661, 671  
Buck 649  
Bullwinkel 11, 132, 146, 147, 200, 201, 203, 205, 222, 250, 251, 252, 253, 258, 259, 260, 263, 269, 300, 301, 304  
Butler 119, 192, 484, 485

## C

Calidonio 495  
Call 661, 671  
Calland 634  
Camesasca 336  
Campbell 11, 13, 97, 98, 99, 100, 102, 117, 118, 132, 139, 140, 141, 146, 147, 149, 151, 171, 200, 201, 203, 204, 205, 222, 250, 251, 252, 253, 258, 259, 260, 263, 269, 270, 279, 287, 297, 298, 299, 300, 301, 304, 317, 318, 319, 338, 445, 657, 705, 706, 707, 708, 709, 712, 713  
Canedo 374  
Carley 254, 255, 256, 272, 292, 388, 391, 481  
Carlson 11, 205, 222, 279, 317, 318, 319, 657  
Carnahan 28, 46  
Carreau 104, 255  
Çengel 150  
Ceraso 332  
Chang 257, 333  
Chella 334  
Chempath 338  
Chen 25, 144, 349, 498, 501

Cheng 11, 205, 222, 250, 251, 252, 253, 259, 260, 263, 297, 298, 299, 300, 301, 302, 304  
 Cheung 32  
 Chiruvela 258  
 Cho 119, 121, 212, 213, 333  
 Christiano 176, 632  
 Christie 408  
 Chum 24, 32  
 Chung 6, 119, 121, 199, 212, 213, 227, 235, 255, 353, 375, 377, 378, 388, 389, 400, 419, 536, 542, 572, 575, 592, 626, 635, 657, 663  
 Cieslinski 27  
 Clap 257  
 Clarke 379  
 Clegg 377, 663  
 Cleven 332  
 Cohen 24, 51, 68, 70, 101, 119, 121, 124, 189, 194, 196, 227, 376, 533, 572, 695  
 Collias 132  
 Conant 16  
 Conner 498, 515  
 Connor 337  
 Costa 661, 671  
 Cox 94, 446, 451, 454, 541, 542  
 Coyle 258  
 Crabtree 119, 121, 152, 195, 197, 200, 212, 442, 445, 447, 574, 587, 601, 695  
 Crawford 116  
 Cross 104  
 Cubberly 151  
 Curtiss 76

**D**

Dai 363  
 Darnell 115, 134, 137, 138, 140, 143, 151  
 Darus 486  
 David 365, 367  
 Davis 174, 177, 178, 646  
 Dealy 76, 93, 100, 101  
 Degee 25  
 deGroot 100  
 Dekker 228  
 Dennis 333  
 Derezhinski 112, 167, 442, 446, 454, 729  
 Devellian 368  
 de Waele 103  
 Dey 662  
 Dhib 53  
 Donovan 199  
 Dontula 11, 13, 139, 140, 141, 151, 205, 222, 258, 259, 263, 269, 270, 279, 304, 705, 706, 707, 708, 709, 712  
 Dooley 11, 119, 124, 160, 164, 203, 257, 279, 351, 352, 447, 451, 461, 498, 515, 636, 637, 638, 640, 641  
 Dray 355, 626, 649  
 Dubois 25  
 Duvdevani 194, 199, 203, 208, 446  
 Dyer 257

**E**

Eccher 257  
 Edmondson 446  
 Edwards 333, 346, 347  
 Effen 596  
 Eirich 100  
 Elbirli 200, 218, 226, 258  
 Elemans 332, 376  
 El-Kindi 377, 663  
 Embirucu 661, 671  
 Epacher 33, 51  
 Erwin 337, 353  
 Esseghir 257, 258, 365, 367

**F**

Fan 614, 634  
 Fasano 371  
 Felton 11, 205, 222, 250, 258, 259, 304  
 Fenner 199, 256, 257, 388, 446, 451, 454, 541, 542, 666  
 Ferry 77, 102  
 Finlayson 11, 254, 255, 256, 267, 304, 306  
 Fogarty D. 680  
 Fogarty J. 680  
 Fogler 408  
 Fontan 53  
 Fox 100, 101  
 Franjione 661, 671  
 Frankland 161, 596, 650, 651  
 Franzkoch 176, 177, 178  
 Fraser 258  
 Frencham 28, 46  
 Fritz 25  
 Fujiki 377, 663  
 Fujiyoshi 26  
 Fukase 200, 203  
 Furches 374

**G**

Gailus 353  
 Galaktionov 368, 369, 370  
 Gale 329, 332, 365  
 Gao 235  
 Garcia-Meitin 486  
 Germano 248  
 Geyer 626  
 Ghosh 333  
 Giles 192, 419, 442  
 Gilette 132, 146, 147  
 Gilmor 495  
 Gleissle 96  
 Gogos 69, 102, 103, 124, 228, 294, 302, 365, 367, 482, 578  
 Golding 661  
 Gore 255, 256, 297  
 Gottgetreu 200, 226

Gould 408, 465, 468  
 Gramann 174, 177, 178  
 Gratch 100  
 Gregory 355  
 Griffith 256, 257  
 Grob 495  
 Grout 368  
 Grünschloß 175, 178  
 Guerra 485  
 Guerrieri 661, 671  
 Guo 388  
 Gupta 119, 121, 152, 195, 197, 200, 212, 213, 445, 447, 574, 587, 601, 695

**H**  
 Halasz 199  
 Hall 119  
 Halley 25  
 Halmos 199, 204, 221  
 Hamielec 53  
 Han 349, 356, 629  
 Hanhart 388  
 Hara 116  
 Harrah 175  
 Harris 26  
 Hassager 76  
 Hasson 257  
 Hattori 26  
 Headley 492  
 Heaney 379  
 Hemsley 486, 487  
 Heniche 371  
 Hennessey 119  
 Hiemenz 42  
 Hiltner 32  
 Himmelblau 442  
 Hindmarch 365  
 Hinton 140, 151, 158, 172, 578, 705, 708  
 Ho 33  
 Hoang 53  
 Hoenig 28, 46  
 Hoffmann 578  
 Hogan 119, 121, 212, 213, 639, 643, 645  
 Hong 119, 121, 212, 213  
 Hook 646  
 Hovis 479, 499  
 Hrymak 373  
 Hsieh 33  
 Hsu 626  
 Huck 377, 663  
 Hudak 649  
 Hughes 110, 116, 117, 160, 171, 365, 366, 367, 578, 651, 705  
 Hunt 259, 298  
 Hunter 333  
 Hyun 11, 110, 112, 113, 116, 117, 119, 120, 121, 122, 124, 131, 139, 140, 142, 150, 151, 152, 154, 158, 160, 164, 171, 172, 189, 194, 196, 203, 225, 227, 231, 237, 257, 279, 330, 351, 352, 376, 392, 447, 451, 461, 466, 467, 498, 515, 533, 541, 542, 543, 545, 548, 572, 574, 578, 595, 598, 636, 637, 638, 640, 641, 695, 705, 706, 708, 710

**I**  
 Iluuta 26  
 Ingen Housz 174, 176, 177, 200, 203  
 Ingen-Housz 365, 367  
 Isayev 3, 462, 514  
 Isherwood 541, 542  
 Ito 26, 101

**J**  
 Jacobsen 25  
 Jaluria 257, 258  
 Janssen 334  
 Jenkins 119, 231, 237, 545, 695  
 Jepson 124, 254, 313, 314, 595  
 Jerome 25  
 Jia 178  
 Jin 178, 235, 236  
 Johnson 33, 368  
 Jons 492  
 Jung 314  
 Juvinall 421

**K**  
 Kacir 230  
 Kamal 3, 462, 514  
 Kang 373  
 Karlbauer 356, 393  
 Karwe 257  
 Kaufman 336  
 Keum 314, 446  
 Khariwala 32  
 Kim 119, 121, 124, 212, 213, 314, 333, 336, 626, 639, 643, 645, 658  
 Kirkland 6, 536, 635  
 Kirkpatrick 119, 120, 131, 150, 152, 231, 542, 695  
 Kisiansky 661, 671  
 Klein 8, 14, 131, 134, 135, 138, 139, 140, 143, 151, 194, 196, 199, 200, 201, 202, 203, 205, 207, 208, 211, 212, 214, 218, 222, 226, 227, 234, 235, 254, 256, 257, 286, 287, 303, 306, 356, 375, 376, 446, 541, 542, 551, 572, 575, 596, 712, 722, 724, 725, 726, 727, 730, 750  
 Klenk 194  
 Kodjie 485  
 Koppi 332  
 Koyama 362, 363  
 Kramer 124, 437, 440, 546  
 Kreith 151  
 Krohnke 33, 51  
 Kruder 388, 614, 633, 634  
 Kuhman 645, 646  
 Kumari 26

Kunio 200, 203  
 Kurata 69  
 Kwade 116

## L

Lacher 218, 625  
 Ladin 126  
 Lafuente 53  
 Landel 77, 102  
 Larachi 26  
 Larson 76, 645, 646  
 Laurence 248, 295  
 Lawrence 626, 649  
 LeBlanc 408  
 Leder 34  
 Lee 228, 349, 356, 629  
 Lepore 651  
 LeRoy 354, 355  
 Liauw 53  
 Lightfoot 261  
 Lin 257  
 Lindt 200, 203, 218, 226, 258, 333, 498, 501  
 Ling 337  
 Liu 3, 25, 462, 514, 596  
 Liu R. 235, 236  
 Liu T. 235, 236  
 Lobo 124  
 Lodge 42  
 Loshaek 100  
 Lounsbury 419

## M

Mack 374  
 Macosko 76, 80, 84, 92, 97  
 Maddock 110, 193, 194, 199, 355, 418, 419, 453  
 Mager 408  
 Maillefer 218, 223, 361, 625, 663  
 Mallouk 254, 255, 256, 272, 292, 297  
 Maloney 671, 672  
 Malvern 261, 293, 294, 295, 304  
 Manas-Zloczower 329, 336, 365  
 Maraschin 661  
 Marshall 446  
 Marshek 421  
 Matsuoka 257  
 McClelland 119  
 McCullough 124, 125, 390, 409, 567, 599, 605  
 McKelvey 254, 255, 256, 272, 292, 297, 303, 388  
 McManus 53  
 McNally 332, 379  
 Meijer 174, 176, 177, 200, 203, 334, 368, 369, 370, 371, 372, 373  
 Meister 98  
 Menges 176, 177, 178, 194  
 Merz 94  
 Metzner 287  
 Miaw 257

Middleman 83, 255, 297, 302, 303  
 Mihara 377, 663  
 Miller 133  
 Moffat 346  
 Mohr 254, 255, 256, 257, 297  
 Mokhtarian 337  
 Mol 115, 134, 137, 138, 140, 143, 151  
 Molnar 199  
 Mondcai 199  
 Moore 124, 332  
 Morgan 479, 499  
 Morrison 76, 81, 83, 688, 690  
 Mount 119, 121, 192, 227, 419, 442, 572, 592  
 Moysey 141, 143, 144, 145, 146  
 Murakami 125  
 Murphy 332, 379  
 Myers 365, 366, 367, 421, 427, 639, 641, 643, 645, 652

## N

Nagarajan 118  
 Naguib 126  
 Naumovitz 237, 545  
 Nazrisdoust 279, 657  
 Nelb 119, 518, 695  
 Nichols 388, 634  
 Nomura 200, 203  
 Norden 365, 367  
 Noriega 174, 177, 178

## O

Ober 24, 51, 68, 70, 101  
 Ogando 537  
 Oka 125  
 Okamoto 26  
 Osswald 174, 177, 178  
 Ostwald 103  
 Ottino 334

## P

Pan 178  
 Paquet 24  
 Park C. B. 126  
 Park S. 126  
 Parnaby 112  
 Patal 314  
 Patterson 119, 180, 181, 518, 695  
 Paul 116, 333  
 Pavlicek 442, 447  
 Pearson 199, 204, 221, 257  
 Peiffer 178  
 Penlidis 53  
 Penumadu 117, 140, 141, 151, 171, 705, 706, 708, 712, 713  
 Perdikoulias 442, 492, 634  
 Pessoa 661, 671  
 Peters 365, 367, 368, 369, 370

Phal 479  
 Pham 447, 467, 548, 595  
 Pinto 256  
 Pittman 255  
 Platt 411  
 Platzer 661  
 Plumley 640  
 Pocius 332  
 Potente 178, 179, 194, 277, 388, 389, 596  
 Powell 377, 378, 657, 663  
 Powers 119, 131, 154, 158, 225, 237, 330, 365, 367, 466, 541, 545, 574, 737  
 Prausnitz 671, 672  
 Prentice 112  
 Prettyman 645, 646  
 Psarreas 53  
 Puhalla 421  
 Pukhanszky 33, 51

**Q**

Qiu 112

**R**

Rabinowitsch 84  
 Rahim 118  
 Ramanathan 492, 661, 671  
 Ramesh 102  
 Raphael 368  
 Rashid 255  
 Rasmussen 102  
 Reber 175  
 Redwine 100  
 Reeder 371  
 Rehg 492  
 Reski 388  
 Reuschle 486  
 Robinson 287  
 Rodriguez 24, 26, 27, 28, 37, 42, 51, 53, 59, 68, 69, 70, 78, 79, 83, 97, 101  
 Rokudai 377, 663  
 Rom-Roginski 495  
 Ronaghan 176  
 Rotem 257  
 Rowell 11, 254, 255, 256, 267, 304, 306  
 Rubens 24  
 Rudin 377, 663

**S**

Salamon 332, 365, 367  
 Sandall 314  
 Sastrohartono 257  
 Sato 125  
 Saucier 76, 93  
 Savargaonkar 485  
 Saxton 254  
 Scheirs 485  
 Schellenberg 34  
 Schlafl 133  
 Schneider 115, 116, 138, 140, 142, 143, 150  
 Schöppner 179, 353  
 Schreiber 377, 663  
 Schrenk 492  
 Schultz 437, 440  
 Schulze 116  
 Schwank 332, 379  
 Schwedes 116  
 Scorah 53  
 Sebastian 228, 578, 662  
 Semmekrot 365  
 Sergent 255  
 Sernas 257, 258  
 Serrano 365, 367  
 Shales 333, 346, 347  
 Shanker 492  
 Shapiro 199, 204, 221  
 Sheth 614, 634  
 Shinnar 257  
 Shinya 200, 203  
 Shishido 101  
 Sickles 133  
 Sikora 175  
 Singh 371, 372, 373  
 Skochdopole 674  
 Slusarz 632  
 Small 118  
 Smith 26, 112, 133, 391, 465, 468, 479, 481, 499, 546, 614, 634, 649, 662  
 Somers 203, 351, 352, 365, 367, 636, 637, 638, 640, 641, 651  
 Spalding 11, 110, 112, 113, 116, 117, 119, 120, 121, 122, 124, 125, 131, 139, 140, 142, 150, 151, 152, 154, 158, 160, 164, 171, 172, 180, 181, 189, 194, 195, 196, 197, 200, 203, 204, 205, 212, 213, 222, 225, 227, 231, 257, 279, 287, 317, 318, 319, 330, 336, 351, 352, 365, 366, 367, 376, 390, 391, 392, 409, 442, 445, 447, 451, 461, 465, 466, 468, 498, 504, 515, 518, 533, 541, 542, 543, 567, 572, 574, 578, 587, 598, 599, 601, 605, 636, 637, 638, 639, 640, 641, 643, 645, 646, 651, 657, 695, 705, 706, 708, 710  
 Squires 14, 257  
 Stangland 119, 124  
 Staples 118  
 Starr 257  
 Steward 133, 546, 632  
 Stewart 261  
 St. John 338  
 St. Louis 545  
 Stolp 257  
 Stoughton 479, 499  
 Stowe 132, 146, 147  
 Strand 11, 139, 257, 279, 447, 451, 498, 515  
 Street 193  
 Strub 256  
 Sugden 578  
 Sulzer Chemtech 370, 371

Sumner 365, 367

Svabik 634

Swain 336

Sweeney 11, 13, 205, 222, 250, 258, 259, 263, 269, 270, 279, 304

Swogger 28, 32, 46

Szeri 231

**T**

Tadmor 8, 14, 69, 102, 103, 124, 131, 134, 135, 138, 139, 140, 142, 143, 151, 194, 199, 200, 201, 202, 203, 205, 207, 208, 211, 212, 218, 222, 226, 230, 235, 254, 256, 257, 286, 287, 294, 302, 303, 306, 329, 356, 375, 446, 482, 541, 575, 712, 722, 724, 725, 726, 727, 730, 750

Takahashi 257, 362, 363

Takatani 26

Tang 11, 200, 201, 202, 203, 204, 228, 229, 445

Tanguy 371

Tanifuji 362

te-Riele 11, 205, 222, 250, 251, 252, 253, 259, 260, 263, 297, 298, 299, 300, 301, 304

Thiel 356, 393

Thompson 118, 141, 143, 144, 145, 146, 542, 632

Tobin 408

Todd 124, 125, 314, 365, 367, 391, 481, 578, 658

Trumbull 336, 545

Tsumashima 69

Tucker 314

Tung 248, 295

Tusim 119

Tzoganakis 53, 126, 492

**U**

Uhl 446

Umeya 116

**V**

Valentinotti 257

Valsamis 374

Van Prooyen 377

van Wunnik 332, 376

Van Zulichem 257

Verbraak 200

Vieira de Melo 661, 671

Vlachopoulos 53, 132, 173, 279, 281, 419, 614, 634

**W**

Wagner 119, 131, 175, 192, 330, 419, 442, 466, 578

Wakeman 33

Walia 379

Walker 24, 132

Walsh 126, 391

Wang 11, 13, 32, 139, 140, 151, 178, 200, 201, 203, 205, 222, 250, 251, 252, 253, 258, 259, 260, 263, 269, 270, 279, 297, 298, 299, 300, 301, 304, 336, 365

Weeks 255

Welsh 674

Werling 377, 378, 657, 663

Wheeler 287, 349, 356, 546, 629, 632

Whissler 287

White 314, 333, 446, 658

Williams 77, 102, 388

Womer 133, 175, 431, 546, 634, 649, 651

Wong 235, 236

Wood-Adams 100, 101

Woods 332

Wortberg 175, 495

**X**

Xie 25

Xue 178

**Y**

Yamamuro 117, 140, 141, 151, 171, 705, 706, 708, 712, 713

Yamashita 363

Yang 662

Yao 362, 363

Youngson 119, 518, 695

Yu 25, 365, 367

**Z**

Zafar 578

Zamodits 257

Zawisza 119, 518, 695

Zhang 337

Zhu 53, 144, 235, 236, 349

Zitzenbacher 356, 393

Zoller 126, 391

Zweifel 133

# Subject

## A

abrasive 466  
Abrasive purge 494  
abrupt reduction 512  
absorbed water 53  
abstracted 52  
a cast film 507  
active center 43, 45  
addition polymerization 40  
addition reactions 43  
agglomerated 500  
agglomerates 334, 374  
air bubbles 530  
air-cooled zone 546  
alignment 421, 422  
alkyd resin 41  
alternating current 436  
alternative hypotheses 411, 413  
amorphous 35, 39  
amortized 466  
amperage 435  
analyzing gels 484  
anecdotal information 473  
angular velocity 91, 297, 300  
antioxidants 47, 51, 52, 494  
apparent shear rate 83  
atactic 34  
average channel width 10  
average shear rate 274  
average shear viscosity 274  
axial length 10, 446  
axial pressure 196, 198, 504, 659  
axial pressure profile 216  
axial screw temperature 454

## B

Bagley correction 81, 82  
baker's fold 336, 368  
barrel 1, 421, 445  
barrel axis 422  
barrel cooling 552  
barrel diameter 8

barrel flange 575  
barrel heaters 1  
barrel length 177, 351  
barrel rotation 254, 297, 300, 301, 307, 318  
barrel support 422, 423, 424  
barrel temperatures 403, 415, 442, 443, 452, 611  
barrel temperature setting 409  
barrel wall 223, 452, 611  
barrel zone temperatures 611  
Barr Fluxion ring mixer 365  
barrier 221  
barrier design 626  
barrier flight 219, 223, 224, 509, 625  
barrier-flighted 352  
barrier-flighted screws 507  
barrier melting 190, 218, 415, 507  
barrier screw 218, 223, 225, 520, 521, 629  
barrier section 224, 511, 512  
barrier section melting model 226  
Barr-II 630  
Barr-III 630  
baseline extrusion process 389  
bed thickness 222  
belt sander 458  
best solution 408  
Bingham plastic 65  
black carbonized 518  
black char 47  
black color streaks 525  
black degraded resin 527  
black specks 53, 493, 518, 631  
black streaks 516, 520, 523, 525  
blending 330  
blister mixers 333, 353, 359, 360, 577, 667, 669  
blockage 415, 566, 572  
blocked screens 478  
blowing agent 332, 364  
blow molding 510, 619  
boiling point increase 61  
bottlenecks 591  
boxy 250  
break 425  
breaker plate 478, 482  
breakup 194, 573

bulk density 110, 111, 239, 410  
 bulk temperature 409  
 burned out 432

## C

calibration 432  
 Campbell-Dontula model 143  
 capillary rheometer 80, 687  
 carbonaceous deposit 631  
 carbon specks 501  
 case study 411  
 casing temperatures 544  
 Cavity Transfer Mixer 365  
 ceiling temperature 49, 50  
 change in rate 227  
 channel curvature 256  
 channel depth 8, 223  
 chaotic mixing 336, 338, 339, 341, 344  
 Charles Ross & Son Company 372  
 Chemineer Incorporated 370  
 chrome plated 483  
 chromium 44  
 circulation channel 681  
 clean 431  
 clearance 357, 361, 419  
 coefficients of friction 119, 445, 562  
 cold screw 425  
 cold start 425  
 colligative 61  
 Colmonoy 456  
 color masterbatches 374, 478, 500, 523, 524  
 color streaks 354, 501  
 comonomer 39  
 compaction 110, 112, 195  
 complex viscosity 93  
 component cost 465  
 composition 333  
 compounder 604  
 compounding line 610, 661  
 compression rate 191, 192, 399, 410, 414, 440, 441, 520, 531, 577  
 compression ratio 191, 192, 399, 404, 414, 440, 520, 531, 573, 577  
 concentrate 374, 500  
 concentration 337  
 concentration peaks 343  
 concrete floor 422  
 condensation 53  
 condensation reactions 40  
 conduction pathway 238  
 cone 91  
 cone and plate rheometer 691  
 contamination defects 477, 498, 501, 513, 521  
 continuous screen changers 479  
 continuum statics based models 141  
 control 532  
 control algorithms 554  
 control volume 314, 316, 317

conventional melting 226  
 conventional screw 349  
 conveying rate 164, 165  
 convey solids 560  
 cool 552  
 cooling coils 675  
 cooling extruder 591  
 cooling level 553  
 cooling water 552, 586  
 cooling water flow 544  
 core 251  
 core drag flow 258  
 core rotation 253  
 correction factor  $F_c$  393  
 correction factors 273, 290  
 corrosive 466  
 cost effective 471  
 cotton fiber 490  
 crack 236, 420  
 crammer feeder 615  
 creep 74  
 critical molecular weight 62, 63, 98  
 critical temperature 593  
 cross-channel flow 264  
 cross-channel velocity 262, 265  
 crosslinked 32, 46, 48  
 crosslinked gels 487, 493, 495, 496  
 cross section 351  
 curvature 497  
 curved channels 256  
 cycle time 533

## D

data acquisition 558  
 data acquisition system 417, 544, 554, 565, 570, 584  
 decompression section 577  
 decrease the rate 190  
 deep channel 278, 320  
 deeper channel 438  
 deep screw 301  
 defect 408, 529  
 degradation process 48  
 degradation products 46, 52, 237, 356, 358, 362, 466, 491, 495, 497, 512, 514, 518, 521, 527, 529  
 degree of crystallinity 38  
 dehydrohalogenate 50  
 depolymerize 50  
 design 454, 629  
 design defect 512  
 deterministic chaos 338  
 devolatilization 364, 662  
 die swell 72  
 dilatant 65  
 direct compounding 379  
 direct current 436  
 discharge 350  
 discharge pressure increases 151

discharge pressures 154, 164, 227, 252, 274, 376, 387, 402, 409, 467, 595, 606, 608  
 discharge temperature 227, 297, 302, 317, 318, 319, 375, 401, 409, 442, 445, 451, 542, 593, 597, 598, 608, 609, 614, 628, 648  
 discharge tip 459  
 dispersed 339  
 dispersive 177, 331, 598  
 dispersive mixer 334, 359, 377  
 dispersive mixing 333, 360  
 dissipation energy 36, 58, 67, 205, 211, 212, 222, 297, 300, 304, 305, 306, 307, 621, 676  
 distributive melt mixing 645  
 distributive mixing 178, 333, 362  
 DM2 high-performance screw 235, 524, 633, 645, 646, 647  
 double bond 51  
 Double Wave screws 614, 622, 633  
 downstream equipment 422  
 drag flow 11, 254, 255  
 drag force 600  
 dried properly 514  
 drier 500  
 drive shank 459  
 drying air 499  
 DSB-II 632  
 DSB-III 632  
 dual-cavity screen 479  
 dust 477  
 dust seal 429, 430  
 dye 343  
 dynamic friction 561, 600  
 dynamic mixers 364

## E

Eagle mixing tip 646  
 elastic 73  
 elastic deformation 63, 64  
 electrical component 409  
 electronic filters 433  
 elongate 348  
 elongation 347  
 elongational flow 334  
 elongation rate 333  
 encapsulate 231  
 energy balance 207, 316, 439  
 energy dissipation 66, 248, 256, 301, 302, 303, 304, 315, 354, 611, 616  
 energy equation 257, 277  
 energy flux 511  
 Energy Transfer screws 235, 633  
 engineering design approach 389  
 enhanced mixing 639  
 entrained air 195, 514, 533  
 entrained gas 191  
 entrained solid 387  
 entrapment 477  
 entropy 336

entropy of mixing 335  
 entry 536  
 equipment failures 477  
 ET (Energy Transfer) screws 401, 518, 536, 622, 626, 635, 636, 638, 639, 640, 678  
 Eulerian 259  
 Eulerian reference frame 304  
 excessive wear 511  
 existing experimental data 392  
 exit 536  
 experience 392  
 experimental plan 415  
 exponentially 340  
 extended startup times 470  
 extended wear 575  
 extrudate 477, 602  
 extrudate temperature 320, 417, 623  
 extruder 339  
 extruder diameter 388  
 extrusion trial 554

## F

facing materials 419  
 failed 432  
 failure 596  
 Fc correction factor 289, 292  
 FDM 257, 277, 280, 281  
 feed casing 133, 420, 421, 562, 574, 575, 578, 580  
 feed channel depth 533  
 feed hopper 132  
 feed section 439, 560, 561, 586, 612  
 feedstock pellets 238  
 FEM 257, 277  
 field-weakened 436  
 film interface 347  
 fines 330  
 finite difference 257, 657, 666  
 finite element 258  
 fit-checked 425  
 five-zone melting model 200  
 fixed boundary problem 262  
 flange diameter 583  
 flash evaporate 552  
 flight clearance 375, 581, 598  
 flight radii 321, 496, 497, 498, 499, 517  
 flight starts 8  
 flight undercuts 416  
 flight wear 596  
 flight width 8  
 flood-fed 18  
 flow channels 457  
 flow rate 297  
 flow surging 214, 227, 507, 541, 543, 554, 564, 575, 583, 586  
 fluid element 348  
 fluid flows 250  
 flute 356  
 foaming temperature 674

foreign contamination 488  
 foreign material 477  
 Four-channel Energy Transfer 679  
 four films 210  
 four melt films 204, 221, 721  
 four polymer films 209  
 fragments 234, 350, 354, 357, 363, 572, 592  
 frame indifference 262  
 free helix 250, 251, 259  
 free helix extruder 338, 344  
 free radicals 44, 51  
 freezing point depression 61  
 frequency 437  
 full 3-D equation 393  
 Fusion screws 235, 633, 649

## G

galling 596  
 gas bubble 483  
 Gaussian 60  
 gearboxes 421, 435, 436  
 gear mixer 354, 360, 364, 622, 667  
 gear pump 548, 557, 584  
 gel analysis 485  
 gels 484, 489, 508, 600  
 gel showers 501  
 gel type 478  
 generalized Newtonian method 281, 282, 286, 288  
 general purpose screw 153  
 geometry 454  
 glass barrel 250  
 glass transition temperature 33, 36, 98  
 glassy polymers 37  
 gloss 377, 378  
 gradients 355  
 gravimetric blending 467  
 gray parts 516  
 grinding lathe 458  
 grooved bore extruders 133, 174, 179, 632  
 grooved bore liner 176  
 grooved feed section 178

## H

halo surface defects 515  
 handheld thermocouple measurement 417  
 hard facing 419, 420, 456, 596  
 haze 377, 378  
 heat capacity 123  
 heat conduction 454  
 heat flux 148, 154, 584  
 heat flux sensors 148  
 heat of mixing 335  
 heat soak 425  
 heat transfer 314, 315  
 heat transfer coefficient 124, 313  
 helical 339  
 helical channel 248, 259

helical coordinates 10  
 helix 250, 251, 253, 259  
 helix angle 9  
 helix-driven flow 253  
 helix rotation 253  
 higher compression 535  
 higher modulus 415  
 high-performance 627  
 high-performance cooling screw 678  
 high-performance design 400  
 high-performance screw 235, 349, 519, 528, 568  
 high-pressure event 428  
 high-pressure separator 661  
 high-quality 525  
 high-rate profile 400  
 high scrap rate 520  
 high temperature 586  
 holes 510  
 homogenizing 331, 335, 353, 367, 602  
 homogenous polymers 37  
 hot-stage microscope 484  
 Huggins function 70  
 humidity level 499  
 hydraulic back pressure 464  
 hydrolysis 53  
 hypothesis 411, 413  
 Hyun-Spalding model 142

## I

impact properties 61  
 Improper drying 499  
 improper labeling 477  
 incompletely melted polymer 530  
 incumbent resin 413  
 induced stresses 236  
 inefficiencies 440  
 inert gas 496  
 inertial terms 262  
 initiators 44  
 injectate temperature 463  
 injection-molding 412, 462, 513, 516, 517, 525, 536  
 inlet pressure 549, 584  
 in-line production 332  
 in-plant regrind 466  
 inside diameter 419  
 instantaneous rate 464, 543  
 intensification factor 464  
 interfacial surface area 337, 348, 368  
 intrinsic viscosity 67  
 IR temperature 417  
 isocyanate 41, 42  
 isotactic 34

## K

Kelvin solid 74  
 Kenics mixer 368  
 KMX mixer 371

knob mixer 354, 363  
Kraemer function 70

## L

labor 465  
laboratory frame 268  
Lagrangian frame 11, 259  
land widths 321  
large flight clearance 421  
large radii 520  
large-radii screw 164  
larger flight clearance 580  
lead length 8, 321, 438, 607, 609  
leakage flow 306  
leathery 529  
ledge 575  
levels of gloss 515  
light scattering 62  
liquid additives 364  
liquid injection 360  
local high temperature 521  
local pressure 217  
log normal distribution 98  
loss modulus 93  
low compression ratio 517  
lowest cost provider 465  
low-pressure separator 661, 671, 672  
low viscosities 374  
lubricating oil 419, 429

## M

Maddock melting mechanism 199, 200  
Maddock mixer 333, 509, 632  
Maddock solidification 110  
Maddock solidification experiments 193, 216, 217, 351, 418, 453  
magnetic collection 482  
Mark-Houwink-Sakurada equation 70  
mass rate 206  
masterbatches 374, 375, 523  
material degradation 541  
mathematical models 200  
maximum torque 425, 426  
Maxwell fluid 75  
measurement noise 548  
measuring instruments 416  
melt-conveying channels 221  
melt density 125, 126  
melted mass 156  
melt-fed extruders 279, 657  
melt film 348, 628  
melt film interface 348  
melt film thickness 214  
melt filtration 478  
melt flow index 94  
melt infiltration 217, 234  
melting 189, 351, 352

melting abilities 639  
melting capacity 592, 628  
melting flux 121, 189, 196, 347, 601  
melting mechanism 193, 230  
melting-mixing 374, 644  
melting process 199, 200, 237, 346, 347, 351, 627  
melting rate 121, 212, 227, 442, 721  
melting section 499, 542, 547  
melt pool 216, 217  
melt pump 467  
melt temperature 318, 319  
mesh 479  
Metal fragments 420, 482  
metallocene 44  
metering section 219, 259, 320, 415, 438, 439, 532  
micrometer 416  
milling lathe 461  
milling process 457  
misalignment 421, 422  
mitigating gels 493  
mixer 354, 356, 439  
mixing 190, 321, 330, 338, 346, 347, 351, 352, 353, 367  
mixing device 355  
mixing flight 354, 355, 356, 361, 509  
mixing quality 376  
mixing section 458  
Moffat eddies 321, 346, 497  
molecular branching 97  
molecular weight 57, 58, 67, 97, 98  
molecular weight distribution 46, 57, 58, 97, 98  
molten resin 547  
momentum balance 277  
motor controls 429  
motor current 409, 415, 431, 432, 435, 576  
motor power 592  
motors 436  
moving boundary 260  
moving boundary problem 262

## N

negative pressure gradient 602  
new barrel 521  
new screw design 416  
Newtonian viscosity 58, 62, 82  
nitrogen inerting 496, 673  
non-Newtonian shear rheology 293  
nonorthogonal coordinate transformation 248  
nonreturn valve 365, 462, 521  
number average 58, 60  
numerically 343  
numerical method 288  
numerical simulation 657  
numerical solutions 257

**O**

off-specification 407  
 one-dimensional melting 228, 232, 234  
 operations downstream 543  
 oscillate 584  
 oscillating depth 680  
 oscillation mode 92  
 osmotic pressure 61  
 Ostwald viscometer 68  
 overall stretching 338  
 oversized in diameter 578  
 overspeeding 437  
 oxidation 47, 52, 53  
 Oxidized gels 486  
 Oxygen exclusion 496

**P**

paired flutes 355  
 parison temperature 620  
 partially filled 503, 518, 555  
 particles 340  
 payback time 619  
 pellet 146  
 pelletization 657  
 pendant groups 37  
 periodic undercut 680  
 peroxide 52, 53  
 phase shift 93  
 physical description 199  
 pigment 331, 374  
 pineapple mixer 354  
 pin mixer 354, 362, 598  
 plant and equipment 465  
 plasticate 320  
 plasticating extruders 507  
 plasticating screw 536  
 plastication rate 463  
 plate rheometer 91  
 plating 459  
 plug flow 145  
 polyacetal 53  
 polyamides 41, 42  
 polycarbonate 53  
 polydispersity index 62  
 polyester 41, 53  
 polyethers 42  
 polymer fragments 480  
 polymer viscosity 213  
 polyolefin 484  
 polyolefin-type gels 480  
 polyurea 41  
 polyurethane 41, 53  
 poor housekeeping 477  
 poorly aligned barrel 425  
 potential energy barrier 36  
 power 435, 439, 440  
 power factor 438, 440

power law index 293  
 pressure 14, 97, 567  
 pressure change 215, 482  
 pressure discharge control unit 146  
 pressure-driven flow 272  
 pressure drop 481  
 pressure flow 11, 12, 254, 255, 287, 410, 439, 464  
 pressure flow velocity 267  
 pressure fluctuation 444  
 pressure generation 319  
 pressure gradient 14, 216, 286, 320, 387, 504, 599,  
 604, 609  
 pressure oscillation 566  
 pressure profile 198, 215, 547  
 pressure rating 433  
 pressure sensors 427, 432, 557  
 pressure swing 555  
 pressure transducers 546  
 pressure variation 558  
 pressurization extruder 658  
 primary extruder 675  
 process data 390, 554, 584  
 processing aids 662  
 process stability 444  
 process temperatures 542, 544  
 production efficiency 466  
 production rates 465  
 productivity improvement 623  
 product quality 466  
 product variation 543  
 propagation 44, 45  
 proper equipment 464  
 pseudoplastic 65  
 pseudoplasticity 92  
 pump ratio 441, 593  
 purging 493, 661, 673  
 pushing flight 223

**Q**

quality control 478  
 quality of the mixing 349

**R**

radial bearing 422  
 radicals 52  
 random flow surging 556  
 rate 319, 409  
 rate increase 389, 617  
 rate-limited 468, 591, 597, 614  
 rate surge 567  
 reaction chemistry 40  
 recirculation flow 92  
 reclaim pelletizing 617  
 Recommended Dimensional Guideline for Single  
 Screws 496, 501  
 recrystallize 508  
 rectangular channel 254

recycle stream 114, 477  
 reduced bulk density 399  
 reduced rates 554  
 reduce the cycle time 647  
 redundant pressure sensors 429  
 reference frame 261  
 refurbishment 410, 460  
 regrind 238  
 relaxation time 72, 74  
 relay 432  
 reorganizing solid bed 203  
 reorientation 334, 344, 353  
 reorienting 362  
 residence time 250, 321, 346, 499  
 resin changes 389  
 resin consumption 553  
 resin cost 465, 541  
 resin degradation 192  
 resin deposits 533  
 resin temperature 672  
 resistive temperature devices 447  
 restricted bond angles 335  
 retrofit 362  
 reversible reactions 53  
 Reynolds bearing 231  
 Rheopexy 65  
 root causes 411, 413, 543, 567  
 Ross mixer 368  
 rotating screw 297  
 rotation 259  
 rotational flow 12, 122, 272, 287, 410, 439, 464, 568  
 rotational flow rate 282, 287, 502, 604, 620  
 routine maintenance 419  
 rubbing in 150  
 rupture disk 427, 428

**S**

safety factor 404  
 scale-down 389  
 scale-up 389  
 scaling rules 387, 388  
 scrap rates 541  
 screen packs 478  
 screw 1, 425, 431, 445, 449, 452, 454, 562  
 screw channels 416, 518  
 screw design 595  
 screw manufacturer 456  
 screw modification 460  
 screw root 450, 454  
 screw rotation 238, 253, 259, 265, 270, 297, 300, 318, 723  
 screw rotation analysis 11  
 screw rotation theory 258  
 Screw Simulator 119, 600  
 screw speed 401, 409, 451, 533, 549  
 screw surfaces 561  
 screw temperature 452, 453, 560  
 screw wear 419, 596  
 seals 360  
 secondary extruder 332, 674, 675  
 secondary mixers 331, 353  
 second flight 218  
 selection of equipment 470  
 semicrystalline 39  
 sensitivity analysis 393  
 service life 468  
 shallow channel 301, 438  
 shaping process 591  
 shear rate 82, 83, 84, 362, 375  
 shear refinement 377, 663  
 shear strength 426  
 shear stress 46, 82, 93, 120, 334, 357, 378  
 shear-thinning 82, 287, 318  
 shear viscosity 524  
 sheave ratio 435  
 short barrel 659  
 silver spots 529  
 simple rotational flow 387  
 simulation 396, 401, 402  
 simulation process 391  
 single-flighted screw 526  
 sinusoidal 91  
 sled device 416  
 sleeve rings 365  
 slide valve 673  
 sliding interface 119  
 slip agents 662  
 slipping 671  
 SMX static mixer 371  
 software controls 427  
 solid bed 112, 144, 205, 217, 225, 229, 231, 234, 235, 348, 450, 572, 573, 628, 723  
 solid bed breakup 234, 235, 349, 351, 542  
 solid bed interfaces 210  
 solid bed reorganizes 210  
 solid fragments 353, 355, 603, 626  
 solidification experiment 196, 199  
 solids 350, 359  
 solids blocking 551  
 solids channel 219, 221, 223  
 solids conveying 132, 134, 143, 462, 542, 560, 563, 576, 581, 600, 603  
 solids conveying device 146, 158, 162  
 solids conveying models 139, 705  
 solids conveying rates 161  
 solids-conveying zone 499, 544  
 solids forwarding angle 136, 138  
 solution viscosity 67  
 specification of equipment 471  
 specific energy 396, 439, 440  
 specific rate 225, 320, 321, 443, 502, 532, 616, 644  
 specific rotational flow rate 529  
 SPI guideline 423  
 spiral channel 429  
 spiral dam mixers 333, 353, 354, 361, 362, 526, 530, 534, 535, 536, 572, 573  
 splay 412, 500, 513, 516

splay problem 536  
 spontaneous mixing 335  
 stability 443  
 stabilization 47  
 stabilizer 52  
 stabilizers 53, 662  
 stable operation 559  
 stagnant regions 223, 491, 495, 512, 527  
 stainless steel 456  
 standing waves 92  
 starve-fed 604, 660  
 static mixer 367, 368, 372, 467  
 statistical analysis 413  
 steady-state temperature 449  
 step reactions 40  
 stereo structure 34  
 storage modulus 93  
 strain 74  
 strain hardening 433  
 strain rate 64  
 Stratablend 650  
 stream stripping 665  
 stress 64, 74, 91, 362, 600  
 stress refinement 377  
 stretching 336, 337, 339, 340  
 stretching rate 333  
 stretch performance 507  
 striations 336, 347, 348, 363  
 stripping agent 364, 593, 662  
 superposition principle 78  
 supersaturated 671  
 surface defects 414  
 surface flaws 585  
 surface temperatures 561, 564  
 syndiotactic 34

**T**

target rate 387  
 technical solution 411  
 temperature 97, 98, 297, 300, 301, 303, 306, 308, 315, 354, 445  
 temperature calculation 314  
 temperature control 542, 544, 553  
 temperature gradient 154, 332  
 temperature increase 259, 314  
 temperature sensor 148, 567  
 temperature zones 442  
 tensile strength 61, 426  
 termination 44, 45  
 thermal conductivity 124  
 thermal expansion 423, 424  
 thermal gradients 332, 333, 353, 363, 367, 446, 514, 675, 676  
 thermocouples 432  
 thixotropy 65  
 three-dimensional numerical method 282  
 thrust 157  
 time-dependent 72

tools 416  
 torque 91, 157, 435, 436, 592, 614  
 torque balance 138  
 total mass flow 15  
 tracer particle 144, 145  
 trailing flight 145  
 transfer line 491, 567  
 transformed frame 267, 268  
 transformed velocity solutions 267  
 transient process data 549, 570  
 transition section 206, 218, 439, 441, 517, 612, 721, 723  
 transverse barrier 224  
 transverse flow 256  
 trap 354, 364  
 trial-and-error design 387  
 troubleshooting 408, 543  
 troubleshooting a process 546  
 troubleshooting problems 15  
 Turbo-Screws 680  
 turbulence 335  
 Twente mixing ring 365  
 twin-screw extruders 1

**U**

Ubbelohde viscometer 68  
 ultracentrifugation 62  
 undercut clearance 357  
 uniform mixing 337  
 Unimix screw 652  
 unit operations 665  
 unmelts 533  
 unmixed gel 508  
 unstable process 548, 559, 571, 585, 615  
 unwrapped 248

**V**

value analysis 466  
 Variable Barrier Energy Transfer screws (VBET) 633, 641  
 vectorial velocities 209  
 velocity profiles 256  
 vent diverter 595, 617  
 vent flow 593, 619  
 vinyl polymerization 40  
 viscoelastic 72  
 viscoelasticity 58  
 viscoelastic model 75  
 viscoelastic properties 73  
 visco seal 430, 669, 670  
 viscosity 57, 64, 335, 375  
 viscosity average molecular weight 71  
 viscosity ratio 374  
 viscous 73  
 visualization 250  
 voids 510  
 Voigt solid 74  
 volumetric flow rate 271

**W**

water cooling 546  
wave screws 235  
wear 422, 575  
weight average molecular weight 58  
welded material 461  
whirling process 457  
wiper flight 356  
wiping 681

wire diameter 479  
wire shielding 434  
worn feed casing 583  
worn screw 598  
wrong resin 478

**Z**

Ziegler-Natta catalyst 44  
zone screw temperatures 545